Guidance Manual for Constructed Wetlands

R&D Technical Report P2-159/TR2

J. B. Ellis, R.B.E. Shutes and D.M. Revitt

Research Contractor:
Urban Pollution Research Centre
Middlesex University, London

Publishing Organisation
Environment Agency, Rio House, Waterside Drive, Aztec West, Almondsbury, BRISTOL, BS32 4UD
Tel: 01454 624400 Fax: 01454 624409
Website: www.environment-agency.gov.uk

ISBN 1 844 321185

Dissemination Status
Internal: Released to Regions
External: Released to Public Domain

Statement of Use
This Guidance Manual is for use by Environment Agency operational staff and others involved in the control and management of surface water runoff from development, and those who are seeking advice on the construction and operation of constructed wetlands to treat road runoff.

Keywords
Constructed wetlands, reedbeds, urban stormwater runoff, urban runoff quality control, sustainable drainage systems (SuDS), urban catchment management, decision support systems, multicriteria assessment.

Research Contractor
This document was produced under R&D Project P2-159 by:
Urban Pollution Research Centre, Middlesex University, Bounds Green Road, London, N11 2NQ Tel: 02 08 411 5000 Fax: 02 08 411 6580 Website: www.mdx.ac.uk

Environment Agency's Project Managers
The Environment Agency's Project Managers for Project P2-159 were:
Dr Maxine Forshaw, National Centre for Ecotoxicology & Hazardous Substances
Barry Winter and Doug Mills, Thames Region

Further copies of this report are available from:
Environment Agency R&D Dissemination Centre, c/o
WRc, Frankland Road, Swindon, Wilts SN5 8YF

tel: 01793-865000 fax: 01793-514562 e-mail: publications@wrcplc.co.uk

CONTENTS

Page

ABBREVIATIONS **vii**

GLOSSARY **x**

EXECUTIVE SUMMARY **xiii**

1. INTRODUCTION **1**

1.1 Background and Context 1

1.2 Aim of this Guidance Manual 1

1.3 Wetland Types and Definitions 2

1.4 Constructed Wetlands and Flow Systems 5

1.5 Pocket or Mini-Wetlands 8

1.6 Modular or Treatment-Train Systems 9

1.7 How Wetlands Work 9

1.8 Wetland Classification 13

2. WETLAND DESIGN **15**

2.1 Introduction 15

2.2 Design Criteria 16

2.3 Substrate Structure 24

2.4 Planting Considerations 25

2.5 Pre and Post Treatment Structures 27

2.6 Wetland retrofitting 30

3. WETLAND PERFORMANCE AND COSTS **35**

3.1 Wetland Performance 35

3.2 Performance Indicators 40

3.3 Treatment, Performance and maintenance Costs 42

4. OPERATION AND MAINTENANCE **47**

4.1 Wetland Operation and Maintenance Requirements 47

5. WILDLIFE AND LANDSCAPE ENHANCEMENT **53**

5.1 Multifunctional Use of Urban Wetlands 53

5.2 Landscape and Visual Issues 53

5.3 Landscape Development 54

5.4 Wetland Wildlife Considerations 56

6. SUDS IMPLEMENTATION AND CATCHMENT PLANNING **59**

6.1 Introduction; The Need for Integrated Approaches 59

6.2 SuDS and the EU Water Framework Directive 59

6.3 Implementing SuDS within River Basin Management Planning 61

7. DECISION SUPPORT APPROACHES **63**

7.1 Introduction: Towards a Multi-Criteria Approach 63

7.2 Defining Primary Criteria, Indicators and Benchmarks 63

7.3 Applying a Multi-Criteria Approach 63

7.4 Benchmark Indicator Standards 63

7.5 Matrix Approaches 66

7.6 Wetland Design Procedure 66

8. RECOMMENDATIONS FOR FURTHER RESEARCH **68**

KEY DOCUMENTS **70**

APPENDICES

Appendix A Wetland Processes 72

Appendix B Wetland Pollutant Efficiency Rates 77

Appendix C Kinetic Design Modelling of Wetlands 80

Appendix D Surface Water Discharges, Sediment Quality Standards and Receiving Water Classification in England & Wales 84

Appendix E Outline Inspection Sheet: Wetland Operation, Maintenance & Management 89

List of Tables

Table 1.1a	Wetland Pollutant Removal Mechanisms and their Major Controlling Factors	11
Table 1.1b	Relative Importance of Wetland Pollutant Removal Mechanisms	11
Table 1.2	A Process-based Classification of Constructed Wetlands	14
Table 2.1	Plant Species Commonly Used in Constructed Wetlands	26
Table 2.2	Summary of the Main Methods Used to Establish the Common Reed (***Phragmites australis***)	27
Table 3.1	Percentage Pollutant Removals for Domestic Wastewater and Artificial Stormwater Wetland Systems in the UK	35
Table 3.2	Wetland Metal Removal Efficiencies for Natural and Artificial Wetlands in the UK	37
Table 3.3	SuDS Pollutant Removal and Flow Attenuation Capacities	41
Table 3.4	Wetland and Dry/Wet Storage Basin Indicators	40
Table 3.5	Distribution of Wetland Capital Costs	43
Table 3.6	Capital and Maintenance Costs for Highway Treatment Systems	44
Table 7.1	Sustainability Criteria and Indicators for Urban Wetlands and SuDS	64
Table 7.2	SuDS Technology Evaluation Matrix	66
Table Appendix B1	Solid Sizes and Settling Velocities	77
Table Appendix B2	Pollutant Load Fractions Attached to Stormwater Solids	78
Table Appendix D1	Standards for Intermittent Discharges	85
Table Appendix D2	Fundamental Intermittent Standards for Ecosystem Types	86
Table Appendix D3	Pollutant 99 Percentile Values for RE Classes	86
Table Appendix D4	Sediment Quality Standards	88

List of Figures

Figure ES1	Major components of On-Line Constructed Wetland	xv
Figure ES2	Major components of Off-Line Constructed Wetland	xvi
Figure 1.1a	SF Constructed Wetland Design	6
Figure 1.1b	SF Constructed Wetland Illustrative Cross-section	7
Figure 1.2a	A SSF Constructed Wetland	8
Figure 1.2b	A SSF Constructed wetland Illustrative Cross-section	8
Figure 1.3	Nitrogen Transformation in a Wetland System	10
Figure 2.1	Linkages and Interactions between Wetland Design Elements	17
Figure 2.2	Wetland Treatment Storage Volumes	20
Figure 2.3	Section through a Sub-surface Constructed Wetland	22
Figure 2.4	Idealised layout of a Constructed Wetland	29
Figure 2.5	Original On-stream Wet Retention Balancing Pond before Retrofitting	32
Figure 2.6	Flood Balancing Pond Following Retrofitting to Incorporate a Constructed Wetland	32
Figure 2.7	Section Through Retrofitted Constructed Wetland	33
Figure 2.8	Retrofitting a Dual Outlet to a Flood Storage Pond	34
Figure 3.1	SSF Wetland Performance Costs	42
Figure 4.1	Predicting Sediment Removal Maintenance Requirement Time	48
Figure 5.1	Schematic Landscaping for a Wet Retention and Wetland Basin	55
Figure 5.2	The Great Notley Garden Village Wetland	56
Figure 6.1	RBMP Programme of Measures	60
Figure 7.1	Multi-Criteria Analysis for the Evaluation of Urban Runoff Control and Treatment Options	65
Figure 7.2	Process Diagram for the Design of Constructed Wetlands	67

Figure Appendix A1 Solids Retention Under Differing Discharge and Volume Conditions 72

Figure Appendix A2 Solids Retention Curves for Three Wetland Sites 73

Figure Appendix C1 Bacterial Removal Efficiency and Hydraulic Loading Rate 83

Figure Appendix D1 Water Quality Assessment Schemes 89

List of Plates

Plate 1 View of Pond F/G looking towards the outlet, with the A34 (Newbury Bypass) in the background. Retro fitted sub-surface flow wetland and balancing pond. xviii

Plate 2 Overview of Pond B looking towards the inlet, alongside the A34 (Newbury Bypass). Surface flow constructed wetland and balancing pond. xviii

Plate 3 A constructed wetland within a commercial development in Milton Keynes, providing flood storage, pollutant treatment and aesthetic amenity value. xix

Plate 4 Vegetated balancing pond at Aztec West Business Park, near Bristol, with ecological features and aeration. xix

ABBREVIATIONS

AMP	Asset Management Plan
ASPT	Average Score Per Taxon
AONB	Area of Outstanding Natural Beauty
BAP	Biodiversity Action Plan
BMWP	Biological Monitoring Working Party
BOD	Biochemical Oxygen Demand
BMP	Best Management Practice
BPEO	Best Practicable Environmental Option
CESM3	Civil Engineering Standard Method of Measurement
CIRIA	Construction Industry Research & Information Association
COD	Chemical Oxygen Demand
CSO	Combined Sewer Overflow
CW	Constructed Wetland
DEFRA	Department of Environment, Food and Rural Affairs
DETR	Department of Environment, Transport and the Regions
DO	Dissolved Oxygen
DTLR	Department of Transport, Local Government and Regions
ED	Extended Detention Basin
EMC	Event Mean Concentration
EIA	Environmental Impact Analysis
EPSRC	Engineering and Physical Sciences Research Council
EQI	Environmental Quality Index
EQS	Environmental Quality Standard
FWR	Foundation for Water Research

GQA	General Quality Assessment
HLR	Hydraulic Loading Rate
HRT	Hydraulic Retention Time
IPPC	Integrated Pollution Prevention and Control
IRBM	Integrated River Basin Management
LCP	Local Contribution Plans
LEAP	Local Environment Agency Plan
LNR	Local Nature Reserve
MIPS	Material Intensity per Service Unit
MTBE	Methyl Tertiary Butyl Ether
NGO	Non-Government Organisation
NNR	National Nature Reserve
NOEC	No Observable Effect Concentration
NWC	National Water Council
O&M	Operation & Maintenance
OFWAT	Office of Water Services
PAH	Poly-Aromatic Hydrocarbons
PAN	Planning Advice Note
PPGs	Pollution Prevention Guidelines
PPG 25	Planning Policy Guidance Note 25 (DTLR)
RBD	River Basin District
RBMP	River Basin Management Plan
RE	River Ecosystem
RHS	River Habitat Survey
RIVPACS	River Invertebrate Prediction and Classification System

RSPB	Royal Society for the Protection of Birds
RQO	River Quality Objective
SEPA	Scottish Environment Protection Agency
SS	Suspended Solids
SF	Surface Flow Constructed Wetland System
SSF	Sub-surface Flow Constructed Wetland System
SLINC	Site of Local Importance for Nature Conservation
SPA	Special Protected Area
SSSI	Site of Special Scientific Interest
SuDS	Sustainable Drainage Systems
SUDS	Sustainable Urban Drainage Systems (as used in Scotland)
SWO	Surface Water Outfall
TOC	Total Organic Carbon
TPH	Total Petroleum Hydrocarbons
TSS	Total Suspended Solids
UDP	Unitary Development Plan
USEPA	United States Environmental Protection Agency
UKWIR	United Kingdom Water Industry Research
VF	Vertical Flow Constructed Wetland System
WFD	Water Framework Directive
WQO	Water Quality Objectives
WWAR	Wetland Area to Watershed Area Ratio

GLOSSARY

Aspect Ratio	Length to width ratio of a Constructed Wetland
Biochemical oxygen Demand (BOD)	The amount of oxygen consumed by the degradation of organic materials
Bioaccumulation	The uptake or accumulation of a compound by a living organisms as a result of exposure to the compound
Bioavailability	The extent by which an ion or compound is freely available for uptake by living organisms
Biomass	The mass of animals and plants within a habitat measured at a given time
Chemical oxygen demand (COD)	The amount of oxygen consumed by chemical oxidation of organic material
Chlorosis	Pale coloration in plants leaves caused by a failure of chlorophyll synthesis
Consent standard	Licence to discharge wastewater at or better than a standard set by a regulatory authority. UK Water Companies usually have to comply with BOD/TSS/amm-N standards, and possibly with additional nitrate and bacteria standards
Constructed wetland	Artificial wetland engineered to achieve biological and physiochemical improvement in the environment
Derogation	Temporarily deferred designation
Emergent macrophytes	Aquatic plants rooted in the support medium with much of their green parts above the surface of the water
Heavy metal	Metalliferous elements and their derivatives including zinc, lead, copper, iron, mercury, cadmium, cobalt, lead nickel and aluminium
Hydraulic conductivity	The ability of support medium to conduct fluid through the interstices between particles which make up the medium
Hydrophyte	Plant which grows in areas with periodic or continuous flooding

Micro-organism	An organism that is not visible with the naked eye
Nitrification	A two-stage process. Ammonia is first converted to nitrite and then from nitrite to nitrate
Denitrification	A microbial process that reduces nitrate to nitrite and nitrite to nitrogen gas
PH	Scale based on hydrogen ion concentration and ranging from highly acid (1) to highly alkaline (14)
Productivity	The rate of production of biomass
Rhizosphere	Zone of soil immediately around roots and rhizomes and modified by them
Rhizomes	Below ground stem of macrophytes
Rip-rap zone	Area of stones placed directly on the ground to protect locations prone to soil erosion, the stones can vary in size but are usually larger than 100mm
Root zone	The area around the growing tips of the roots of a plant
Support medium	Gravel, soil or other material used as the matrix within the constructed wetland
Suspended solids (SS)	Dry weight per volume of matter retained by a filter
Total suspended solids (TSS)	Material remaining in a sample when all the water has been evaporated

EXECUTIVE SUMMARY

The increase in road construction has highlighted the issue of increased volumes of highway runoff and the potential pollution of groundwater and surface waters. The Environment Agency are involved in the assessment of the effects of urban and highway runoff and mechanisms for the protection of water quality.

Constructed wetland systems have been used extensively for the treatment of municipal, industrial and agricultural effluent, but they have only been recently developed and investigated for the treatment of urban surface runoff. Although, vegetated wet balancing ponds have been used to treat highway runoff, their performance has not previously been assessed in the UK in comparison with constructed wetland systems. The potential for combining constructed wetlands with flood storage ponds would be beneficial in terms of flood alleviation and pollution control. The Halcrow Group Ltd and the Middlesex University Urban Pollution Research Centre were commissioned by the Environment Agency (Thames Region) in 1995 to undertake a Research and Development project to investigate the treatment of runoff by the use of vegetative treatment systems. The project comprised: a literature review; a monitoring programme and the development of an interim manual (Halcrow et al, 1996,1998).

The literature review considered over 150 references and their key points were summarised in the final report The subjects covered included the characteristics of highway runoff and their pollution impacts on receiving water, relevant legislation, and treatment options. The characteristics of highway runoff were found to be highly variable due to varying traffic conditions, lengths of antecedent periods, intensities of storms and volume of rainfall. EU and UK legislation were reviewed and listed. Treatment options considered included gullypots, oil separators and silt traps, detention systems, filtration systems, sedimentation tanks, lagoons and constructed wetlands.

An Interim Manual, the Treatment of Highway Runoff Using Constructed Wetlands was published by the Environment Agency in 1998 and the results of a monitoring programme of a constructed wetland system on the A34 Newbury Bypass has been published in 2003. The aim of the current Guidance Manual is to provide updated information on the design, costs, construction, operation and maintenance of constructed wetlands, including the configuration, planting medium, water levels and type and extent of the vegetation in order to effectively treat urban runoff. In addition, the types of wetland and how they remove pollutants are considered together with their potential for enhancing the landscape and attracting wildlife. Decision support approaches for selecting constructed wetlands as a Sustainable Drainage System (SuDS) treatment option and their implementation are discussed. The information provided in this Guidance Manual is derived from Constructed Wetlands and Links with Sustainable Drainage Systems, R&D Technical Report P2-159/TR1 which includes an updated literature review.

Section 1 of the Guidance Manual includes examples of the various types of wetlands and how they work. Section 2 provides guidance regarding the design and planting of a constructed wetland system and the retrofitting of existing

treatment structures, and in Section 3 the performance and costs of urban wetlands are considered. In Section 4 the operation and maintenance requirements for constructed wetland systems are addressed. The use of wetlands to encourage wildlife and enhance the landscape is considered in section 5 and the implementation of Sustainable Drainage systems (SuDS), including constructed wetlands, and catchment planning in Section 6. The use of decision support approaches for selecting SuDS systems and recommendations for future research form sections 7 and 8.

Feedback on use of the Guidance Manual or monitoring information to establish the effectiveness of constructed wetland systems for the treatment of highway runoff should entered on the HR/EA UK National SuDS base (www.suds-sites.net).

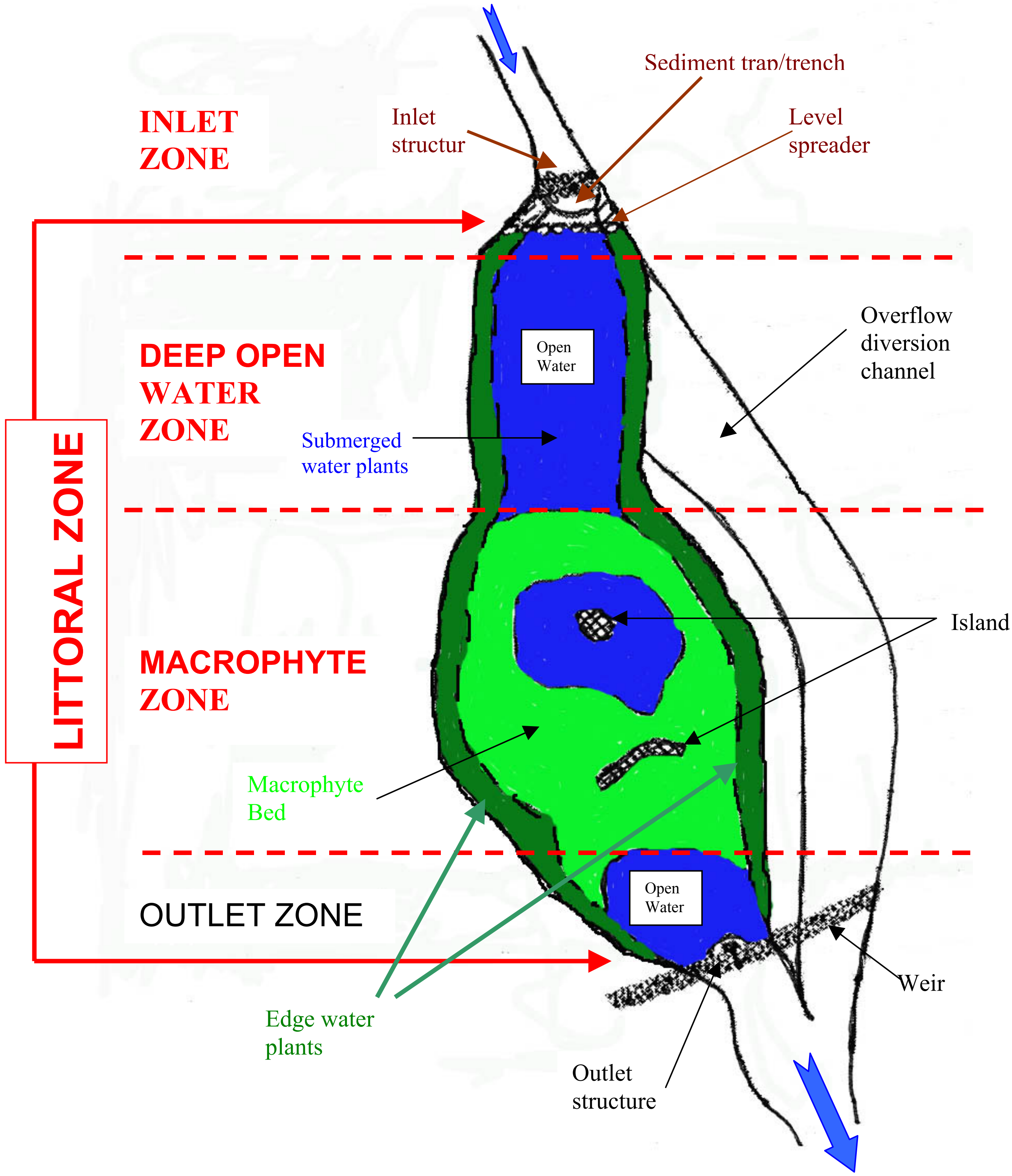


Figure ES1. Major Components of On-Line Constructed Wetland

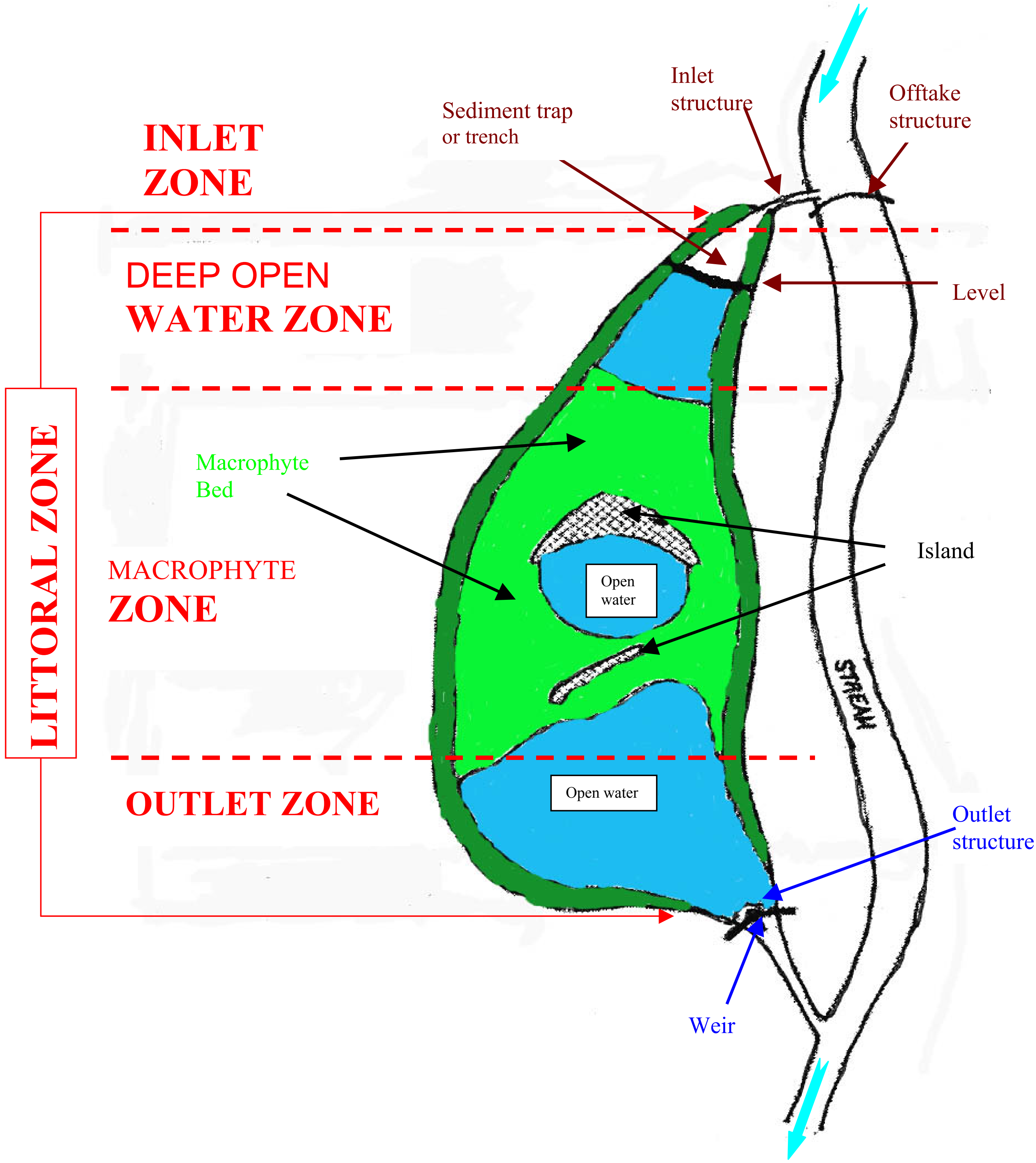


Figure ES2. Major Components of Off-Line Constructed Wetland

Constructed Wetlands - Key Considerations

Design Criteria

- Minimum contributing drainage area of 8/10ha; 1.5/2.0ha for a pocket wetland
- Minimum dry weather flow path of 2:1 (length:width) should be provided from inflow to outflow; avoid short-circuiting
- Minimum of 40 - 50% open water with minimum of 35 - 40% surface area having a depth of 2.5cm; 10 – 15% of surface area should be a deep pool (0.5 – 2.0 m depth)
- Sediment pre-treatment (e.g sediment forebay or pre-settlement pond) of 10 – 15% total wetland cell volume
- Variable wetting-drying cycle to encourage macrophyte growth/diversity; hydraulic retention time of 12 – 24 hours for the design storm event

Advantages/Benefits

- Good nutrient, bacterial, oil and solids removal
- Can provide natural wildlife habitat and public amenity feature
- Relatively low maintenance costs

Disadvantages/Limitations

- Requires fairly large land uptake
- Needs continuous baseflow (i.e. minimum water level) for viable wetland
- Sediment regulation is critical to sustain long term wetland performance

Maintenance Requirements

- Monitor and ensure initial plant establishment period
- Replace wetland vegetation to maintain at least 35 – 40% coverage
- Remove invasive vegetation
- Monitor sediment accumulation and remove periodically

POLLUTANT REMOVAL

70 - 80%	Total suspended solids; bacteria
40 - 50%	Nutrients
50 – 60%	Heavy Metals
60 - 70%	Oils, hydrocarbons

STORMWATER MANAGEMENT SUITABILITY

- Extreme flood protection
- Receiving water quality
- Downstream channel protection
- Overbank flood protection
- Accepts first-flush runoff
- Requires minimum 0.75 – 2.0 m separation distance to water table

IMPLEMENTATION CONSIDERATIONS

Land requirement: **M - H**
Capital costs: **M**

Maintenance Burden

Shallow wetland: **M**
Extended detention shallow wetland: **M**
Pocket wetland: **M - H**
Wetland/Pond: **M**

Residential/Commercial use
Unsuitable for high density, ultra-urban core areas
Permeable soils will require liner

L = Low: **M** = Moderate: **H** = High

Plate 1. View of Pond F/G looking towards the outlet, with the A34 (Newbury Bypass) in the background. Retro fitted sub-surface flow wetland and balancing pond

Plate 2. Overview of Pond B looking towards the inlet, alongside the A34 (Newbury Bypass). Surface flow constructed wetland and balancing pond

Plate 3. A constructed wetland within a commercial development in Milton Keynes, providing flood storage, pollutant treatment and aesthetic amenity value

Plate 4. Vegetated balancing pond at Aztec West Business Park, near Bristol, with ecological features and aeration

1. INTRODUCTION

1.1 Background and Context

It has been widely recognised for some time that urban runoff, particularly from motorways, contains a range of pollutants that can have detrimental impacts on receiving waters, both ground and surface. The increase in road construction and especially the widening of existing motorways under the Government's `Roads Programme' highlighted the issue of increased volumes of highway runoff and the potential pollution of ground water and surface waters. The Environment Agency are involved in the assessment of the effects of urban runoff and mechanisms for the reduction of deleterious effects in receiving waters.

In recent years the Environment Agency has investigated available treatment methods for urban runoff, which include grass swales, detention ponds and constructed wetlands based on reedbed treatment technology. Particular emphasis has been placed on the consideration of constructed wetlands for urban runoff treatment for a number of reasons, including:

potential for high pollutant removal performance for low capital and operating costs;

capability for treating large volumes of runoff which could not realistically be treated by conventional mechanical methods; and

potential for ecological and aesthetic enhancement opportunities.

Constructed wetland systems have been used extensively for the treatment of municipal, industrial and agricultural effluent. However, the treatment of urban runoff by constructed wetlands has only recently been adopted and investigated.

1.2 Aim

The aim of this Guidance Manual is to provide information on the design, construction, operation and maintenance of constructed wetlands, including the configuration, planting medium, water levels and type and extent of the vegetation in order to effectively treat urban and road runoff.

This Manual includes the following information:

Examples of the various types of Wetlands and how they work (Section 1);

guidance regarding the design and planting of a constructed wetland system and the retrofitting of existing treatment structures (Section 2);

the performance and costs of urban wetlands (Section 3);

the operation and maintenance requirements for constructed wetland systems (Section 4)

the use of wetlands to encourage wildlife and enhance the landscape (Section 5)

the implementation of Sustainable Drainage systems (SuDS), including constructed wetlands, and catchment planning (Section 6)

the use of decision support approaches for selecting SuDS systems (Section 7)

recommendations for future research (Section 8).

The user may only require information on constructed wetland design, operation and maintenance from Sections 2 and 4 with costs from Section 3. However, the Guidance Manual is designed to provide background information to wetlands (Section 1) in addition to the criteria for selecting and implementing them as a SuDS option (Sections 6 and 7). It is hoped that the guidelines for enhancing the landscape (Section 5) will be of use to both engineers and landscape architects.

1.3 Wetland Types and Definitions

1.3.1 Definitions.

Wetlands are a generic term covering a variety of water bodies supporting aquatic vegetation and providing a biofiltration capability. They include not only natural marsh and swamp environments but also artificially constructed storage basins or ponds. Wetlands are essentially transitional between terrestrial and aquatic systems, where the water table is normally at or near the soil surface or where there is a permanent shallow water cover. However, the presence of water by ponding, flooding or soil saturation is not always a good indicator of wetlands as they can often appear to be dry. Nevertheless, wetlands possess three basic characteristics:

- an area supporting (at least periodically) hydrophytic vegetation i.e. plants which grow in water
- substrates which are predominantly undrained hydric (continually wet) soils
- non-soil (rock/gravel) substrates which are either saturated with water or have a shallow, intermittent or seasonal water cover.

1.3.2 Natural and semi-natural wetlands.

Natural wetlands typically exhibit gradual hydroperiods (i.e. variation in water level), complex topographic structures, moderate to high wildlife habitat value, support few exotic species and are self-sustaining. They can be classified into three basic types:

- swamps which are dominated by water-tolerant woody plants and trees
- marshes dominated by soft-stemmed emergent plants such as rushes, reeds and sedges (but which can also contain submergent and floating plants)
- bogs which are characterised by acidic and low-nutrient water and acid-tolerant mosses.

Fir Wood Nature Reserve, Herts
A small natural wetland located near to Junction 24 on the M25 at Potters Bar receives soil-filtered runoff from the motorway. Although aqueous metal levels recorded in the wetland are well below statutory water quality standards, metal sediment levels show moderate to high levels of contamination.

Although natural wetlands and their surrounding riparian area reduce diffuse pollution, they do so within a definite range of operational conditions. When either hydrologic or pollutant loadings exceed their natural assimilative capacity, they rapidly become stressed and degraded.

It is also possible to recognise a separate category of semi-natural wetlands that have developed in open water situations after colonisation by aquatic vegetation. Such semi-natural, self-seeded wetlands can be found in open waters initially designed as flood storage reservoirs (retention/detention basins) or ornamental ponds in urban areas. They also quite frequently occur in disused gravel pits, silt and ash (PFA) lagoons (Merritt, 1994). The Ruxley gravel pits adjacent to the River Cray in Kent and the Great Linford pits on the upper Ouzel in Milton Keynes are also examples of self-seeded, wetland marshes. Both are important nature reserves and community assets and also have significant functions as stormwater balancing facilities.

The Welsh Harp, N W London
The Welsh Harp basin, whilst originally constructed as an ornamental reservoir, now serves as a storm runoff attenuation facility for the highly urbanised 5.2 km^2 Silk Stream catchment, with some 60% of the annual flow volume being derived from impermeable surface runoff. The wet retention basin has an extensive *Typha* and *Phragmites* wetland marsh located at the inlet which has become an important wildfowl and bird reserve. Studies have shown that this semi-natural wetland functions as an effective pollution control facility for the treatment of urban runoff removing some 97% of Suspended Solids (SS) and between 50-80% of the hydrocarbons contained in both water and sediment passing through the basin. The Biological Monitoring Working Party (BMWP which assess the macroinvertebrate community status) scores improve from a very depressed value of 5 immediately upstream of the inlet to 50 below the wetland.

1.3.3 Artificial or created wetlands.

Artificially constructed wetland storage basins or ponds which create "generic" wetland habitats, have the more limited objectives of flood and pollution control. Created stormwater wetlands which are dependent on surface water runoff are "semi-tidal" in nature, being continuously exposed to episodic inundation and subsequent drawdown. The extent of the changes in water level impose quite severe physiological constraints on the plant community. The resulting created wetland systems typically have a more clearly defined open water component than natural wetlands. The types of artificial constructed wetlands which can function as urban stormwater facilities include:

Shallow marsh systems requiring considerable space and which drain contributing areas often in excess of 10 hectares. They demand a reliable baseflow or groundwater supply to support emergent wetland plants. The 140 ha Potteric Carr Reserve at West Bessacarr near Doncaster receives surface runoff from a 1261 ha mixed urban catchment, is a very large marsh system. Whilst being a designated nature reserve dominated by carr marsh, it also retains its function as a major flood storage facility. The "water meadows" in the Chells district of Stevenage similarly operate as shallow marshes fed by overbank flows from the Aston End Brook generated by urban surface runoff during storm events.

Rye House Nature Reserve
The 5 ha Rye House nature reserve in the lower floodplain of the River Lea and operated jointly by the RSPB and Thames Water, is an example of a long established constructed shallow marsh. The wetland marsh was created in 1973 taking 90 Ml/day of treated sewage effluent from the adjacent tertiary treatment lagoons of Rye Mead sewage works. The wetland marsh is now managed as a series of compartments demonstrating a range of habitats from shallow pools and scrapes, through reed bed to carr.

Retention or wet (balancing) ponds/basins having a permanent water volume are amongst the most frequently encountered flood storage facilities in the UK for managing and controlling urban and highway runoff. Surface stormwater runoff displaces the water lying in the basin at the commencement of the storm event. Sedimentation within the basin will occur as well as biological uptake and other forms of treatment (volatilisation, complexation, photo-oxidation etc.). Retention ponds can have marginal rooted and submergent/floating aquatic vegetation with open water comprising typically some 50 - 75% of the total basin surface area.

The Ouzel Valley Lakes
The series of wet retention (balancing) lakes located in the Ouzel valley at Milton Keynes contain marginal aquatic vegetation which is partly semi-natural and partly artificially introduced. The largest lakes in this balancing system are Mount Farm Lake (95ha), Willen Lake (87ha) and Caldecotte Lake (44ha). All three are fringed by both emergent and submergent macrophytes which not only provide enhanced ecological and amenity functions, but also help to reduce the elevated nutrient, oil and heavy metal concentrations associated with wet weather urban surface discharges.

Small, semi-permanent (low-lying) marshes and pools have been frequently incorporated into dry detention basins to form an ***extended detention*** (***ED***) basin. Such wetlands (of between 10-25% of the total basin area) facilitate pollutant removal and mitigate against short-circuiting, channelisation and sediment re-entrainement. A few ED basins are now being formally introduced under the SEPA SUDS initiative in Scotland on the Dunfermline (Eastern Expansion, DEX) site in Fife. There is a modified ED basin with a semi-permanent pool as well as a low level wetland marsh in the off-line 38,000 m^3 detention basin located at North Weald, Essex and a number of industrial/commercial estates have extended dry detention basins to incorporate a wet marsh facility. A number of originally dry detention basins have shallow marsh/wetland vegetation occupying some part of the basin floor and now effectively function as extended detention facilities with the vegetation filtering out pollutants contained in the influent surface water flows.

Extended Detention Basins in Essex and Herts
The 65ha Pinnacles Industrial Estate at Harlow, Essex discharging surface water to a 19,400 m^3 capacity storage basin and 10.93 ha of the M11 at Stansted Brook in Hertfordshire which discharges to a 4,900 m^3 capacity dry basin, now have low-level marsh located in the base of the storage facilities.

Combined pond/wetland (retention/detention) basins are storage facilities where part of the containing basin is given over to dead storage (permanent pools) and part to live (fill and drain) storage. Such combined retention/detention wetland designs have been adopted for the control and management of highway runoff as on the A34 Newbury bypass, the A4/A46 Bathford roundabout and at the M49 junction to the east of the southern Severn Bridge crossing. The designs frequently possess a front-end pool or chamber which traps sediment and associated pollutants providing treatment for the first flush and (the more frequent) small runoff events. The wetland cell (which can be separated by a filter strip or gabion wall from the permanent pond), provides for temporary storage, secondary biological treatment and attenuation of runoff from larger more infrequent storms. A final micropool or settlement pond might also be included to give a more limited tertiary treatment.

> **The A34 Newbury Bypass**
> A total of nine flood storage basins have been built alongside the A34 Newbury Bypass to control and treat surface water design discharges varying between 20-120 l/s, from 13.5 km of dual, two-lane trunk road. Maximum design storage volumes vary between 121-676 m^3 with retention times of between 30-120 hours. One storage basin has been retrofitted with a SSF constructed wetland (*Phragmites*) and wet weather removal rates recorded for the wetland system has been high with SS and heavy metal removal efficiencies varying between 40-75% and 59-98% respectively.

> **District Park (DEX), Dunfermline, Fife, Scotland**
> Combined dry/wet retention basins and SF wetlands treat surface water from a 600ha light industrial/commercial and highway catchment. Percentage metal removals from the wetlands are Cu 33%, Pb 25% and Zn 65%. Mean metal sediment levels are Cu 13, Pb 10.5 and Zn 30.2 mg/kg .

1.4 Constructed Wetlands and Flow Systems

1.4.1 Constructed wetlands

Constructed wetland basins normally have non-soil substrates and a permanent (but normally shallow) water volume that can be almost entirely covered in aquatic vegetation. Constructed wetlands may contain marsh, swamp and pond (lagoon) elements; the inlet zone for example, can resemble the latter form and be used as a sediment trap. The dominant feature of the system is the macrophyte zone containing emergent and/or floating vegetation that requires (or can withstand) wetting and drying cycles. Constructed wetlands lack the full range of aquatic functions exhibited by natural wetlands and are not intended to provide species diversity. Whilst natural wetlands depend upon groundwater levels, constructed stormwater wetlands are dominated by surface runoff in a random “semi-tidal” hydroperiod characterised by cyclic patterns of inundation and drawdown.

> **Anton Crescent, Sutton, Surrey**
> The 1.3 ha Anton Crescent wetland in Sutton, Surrey has been built in a wet detention basin which serves a mixed residential and light commercial catchment. The basin has a maximum design storage capacity of 10,000 m^3 with a mean retention time of 10.8 days. The SF constructed wetland was planted with *Typha* to provide a wildlife conservation area and a local amenity/educational facility and now also provides a valuable water quality function with average removal rates for SS, Zn and Faecal Coliforms of 56%, 37% and 78% respectively .High metal levels are associated with the sediments filtered out by the macrophyte roots and stems (Cu 40, Pb 126.6 and Zn 120.7 mg/kg.

Such constructed wetlands typically experience much greater sediment inputs than natural wetlands. In addition to a more restricted aquatic flora, they are likely to provide an environment favourable to invasive terrestrial weed species especially during plant establishment. Open water would normally occupy up to 25 - 30% of the total basin surface area with remaining areas comprising shallows up to a maximum depth of 0.5m. Flood storage can also be added above the treatment wetland where the surrounding terrain permits

Keytec 7 Pond, Pershore, Worcs.
The 10.9ha Keytec Industrial estate pond in Pershore, Worcs was designed as a flow balancing facility with a SF constructed wetland to provide 1500m^3 of stormwater storage with a retention time of 15-20 hours. The imposed pollution discharge consents for SS (100mg/l), BOD (20mg/l) and oils/hydrocarbons (5mg/l) have been successfully met throughout the operational lifetime of the basin.

1.4.2 Constructed wetland flow systems

Although the design of artificially constructed wetlands varies making each system unique, the basic flow configurations can be divided into two categories:
Surface flow (SF) or ***free water surface*** (FWS) systems which are similar to natural marshes in that they are basins planted with emergent, submergent and/or floating wetland macrophyte plants. Such free surface water treatment wetlands mimic the hydrologic regime of natural wetlands. Almost all constructed wetlands in the UK for the treatment of urban runoff comprise surface flow systems and resemble natural marshes, in that they can provide wildlife habitat and aesthetic benefits as well as water treatment. The influent passes as free-surface (overland) flow (and/or at shallow depths) and at low velocities above the supporting substrates. Figure 1.1a and b shows a (3 x 80m) linear SF design which has been retrofitted into a widened stream channel in Dagenham, East London to treat surface runoff from a 440ha residential and commercial area. The 1750m^2 modular wetland system is designed to meet 50% removal efficiencies for targeted pollutants (BOD, Pb, Zn, and SS). SF/FWS systems with low flow rates are susceptible to winter ice-cover in temperate climates such as the UK, and have reduced efficiencies during such times since effective water depth and retention time are reduced .

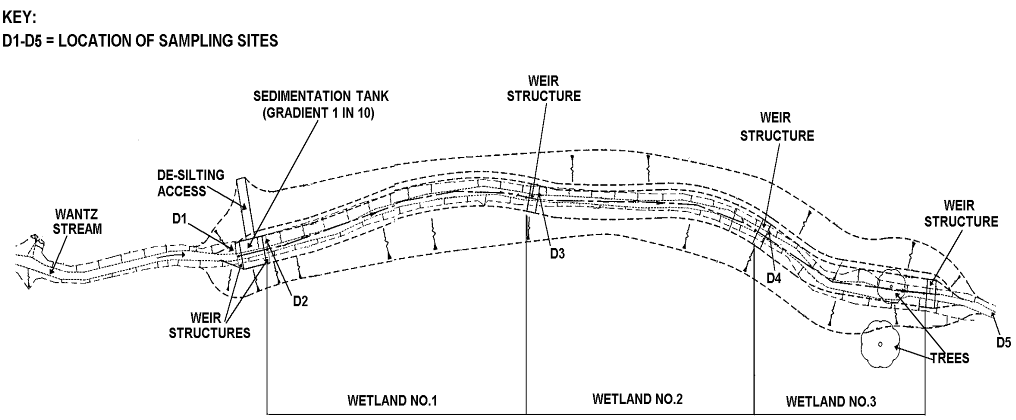


Figure 1.1a. SF Constructed Wetland Design (R Wantz, Dagenham, E London.)

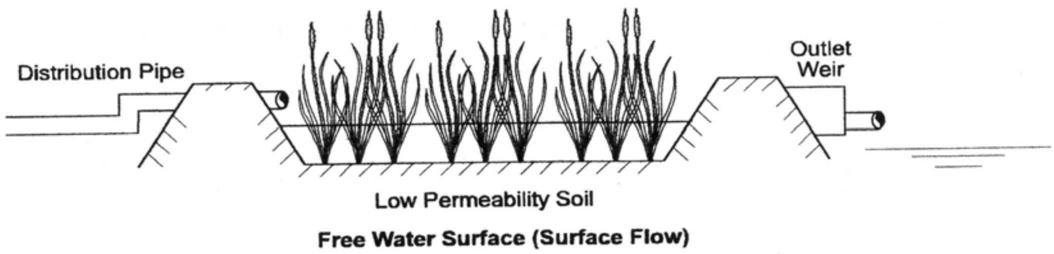


Figure 1.1b. SF Constructed Wetland Illustrative Cross-section (After: Kadlec and Knight, 1996)

Subsurface flow (SSF) systems operate with the influent flowing below the surface of the soil or gravel substrate. Purification occurs during contact with the plant roots and substrate surfaces, which are water-saturated and can therefore be considered to be oxygen-limited. The substrate in these systems is thermally insulated by the overlying vegetation and litter layer and so the wetland performance is not significantly reduced during the winter. Most of the earliest wetland treatment systems in Europe were SSF systems constructed to treat domestic wastewater. There are two basic flow configurations for SSF wetlands:

- horizontal flow (HF) systems where the effluent is fed in at the inlet but then flows slowly through the porous medium (normally gravel) under the surface of the bed in a more or less horizontal path to the outlet zone. These HF systems are also known in the UK as Reedbed Treatment Systems (RBTS) as the most frequently used plant is the common reed (*Phragmites australis*).

- vertical flow (VF) systems, which usually have a sand cap overlying the graded gravel/rock substrate, and are intermittently dosed from above to flood the surface of the bed. The effluent then drains vertically down through the bed to be collected at the base. Such VF systems are similar in design and operation to conventional percolating filters but are very rarely found on surface water drainage systems (Table 1.1).

Figure 1.2a and b illustrates a SSF constructed wetland system located at Brentwood, Essex to treat surface water discharges from a 400ha mixed urban catchment prior to entry into the River Ingrebourne. During high flows, untreated effluent also overflows into a natural *Typha* wetland in addition to passing through the SSF *Phragmites* wetland before final discharge to the river. The total wetland area is 204m^2 and the mean retention time is 50 minutes. Dry weather removals average 30 - 33% for Pb and Cu, 19% for Zn, 18% for SS, 26% for BOD and 50% for total ammonia with mean metal sediment removals varying between 17 - 33% .

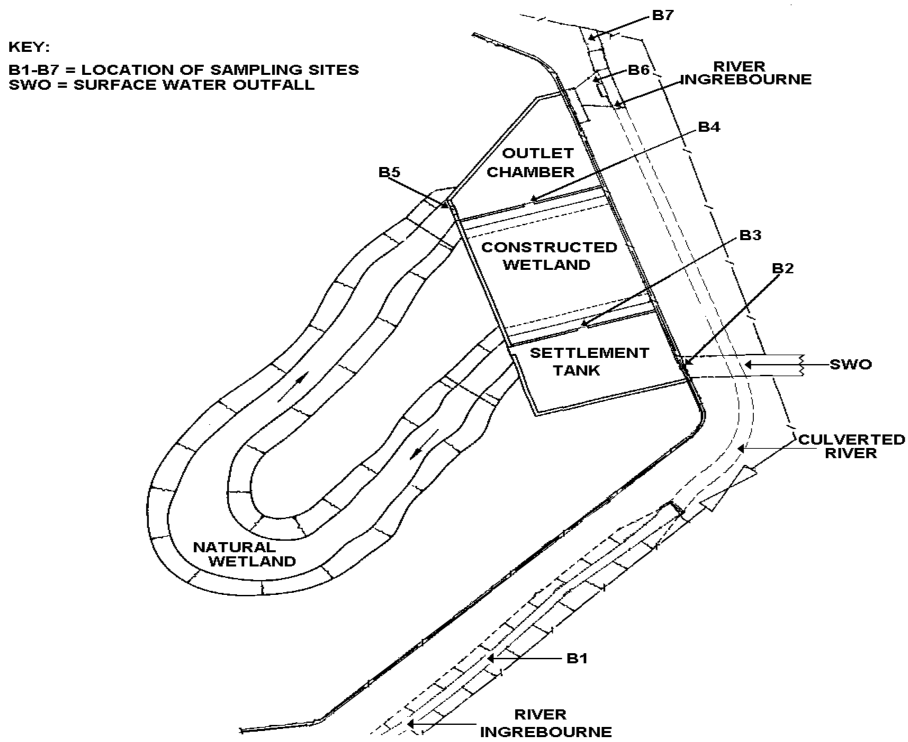


Figure 1.2a. A SSF Constructed Wetland (Brentwood, Essex)

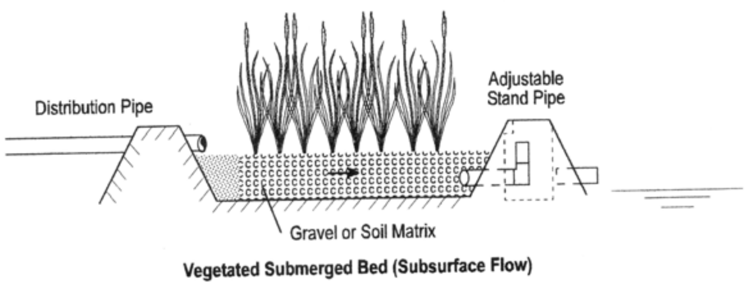


Figure 1.2b. A SSF Constructed Wetland Illustrative Cross-section (After: Kadlec and Knight, 1996)

1.5 Pocket or Mini-Wetlands

A particular form of compact (or pocket) stormwater constructed wetland which has been developed in the eastern United States and which is suitable for small sites of 0.5 - 5.0 hectares. Such pocket wetlands may not have a reliable source of baseflow and thus are subject to large fluctuations in water level.

Welford Mini-Wetland, Leics
A pocket or mini-wetland can be found on the outskirts of the S Leicestershire village of Welford where surface water from the A50 has been drained to support a linear 0.25 ha marsh site immediately adjacent to the highway and which helps to alleviate flooding on a dip in the carriageway. The development was entirely the result of local community effort with technical advice from the Groundwork Trust and provides an aesthetic environmental focus for the village.

1.6 Modular or Treatment-Train Systems

The various types of storage basin all have similar basic design principles. They can be used in-series or as modular cells within a single overall structure and can be adapted to either on or off-line configurations. The module sequencing is important in order to ensure that the primary function of each is sustainable. One effective form of treatment-train might consist of an inlet sediment trap or forebay, followed by a wet retention or dry detention basin which is then discharged to a full wetland system. Islands in open water zones also provide important habitat and landscaping elements.

> **Wharrage Brook, Redditch, Worcs.**
> The Environment Agency Midlands Region has constructed a modular treatment train system downstream of the urbanised section on the Wharrage Brook near Redditch, Worcs. A primary silt trap is followed by wet retention for flow and quality balancing and a final SF reedbed for stabilisation and treatment. The retrofitted design provides a maximum storage capacity of 3500 m^3 and serves a 4km^2 mixed urban catchment. Extensive surrounding landscaping has also provided valuable wildlife habitats and amenity features for the local urban community.

Series (or treatment-train) configurations can help to improve the treatment performance and can be particularly useful on steep sites, sites having several small separate "vacant" areas or in narrow, linear spaces along fields, road edges or river corridors. They can also be used as a basis for retrofitting SuDS components into cramped existing urban developments as evidenced by the restoration scheme in the floodplain of the River Skerne in Darlington . A linear series of small wetlands have also been successfully retrofitted into a ditch carrying the discharges from filter drains on the southern carriageways of the M25 just south of Junction 15 near Heathrow Airport.

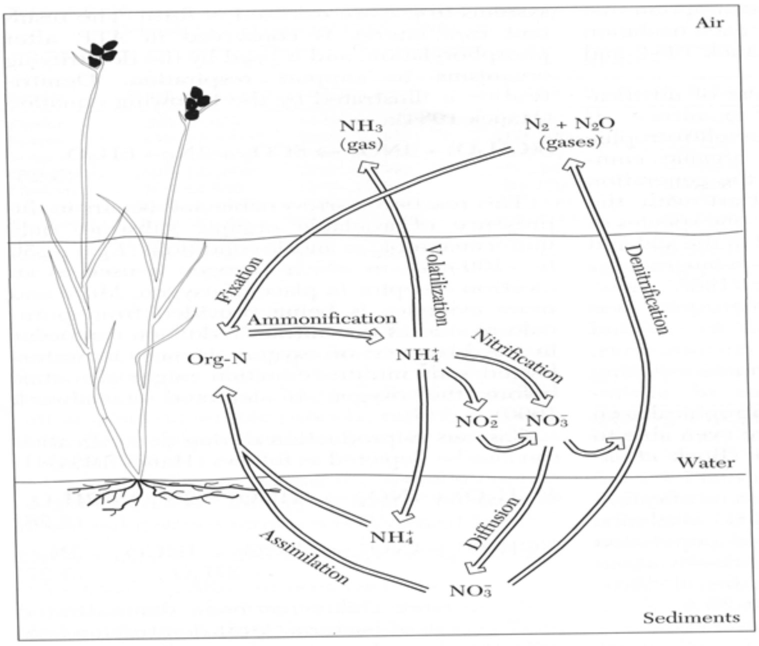
> **Webheath, Redditch, Worcs.**
> A 4 cell modular wetland system preceded by a small sedimentation basin has been recently retrofitted into a 270 housing development site at Webheath, Redditch. The linear reed bed cells (25m x 5m) have been retrofitted into a narrow pre-existing degraded channel on the site and provide a void storage of 50 m^3 per impervious hectare for the initial 5mm of effective rainfall-runoff.

1.7 How Wetlands Work

1.7.1 Introduction

A wetland system consists of biotic (plant, algae and associated fungi and bacteria) and abiotic (surface and interstitial water, sediment and detrital material) compartments. Each of the compartments can serve to differing degrees, as a storage location for pollutants entering the wetland. The vascular plants transfer nutrients, gas and other materials (including pollutants) from one part of the plant to another. The microbial compartment is extremely complex and is probably the least understood although it may be the most important wetland component. The micro-organisms are found in the water column, attached to living and dead organic material and within the detritus that builds up on the wetland substrate. Some (facultative) bacteria can grow in either aerobic or anaerobic environments whilst others (obligate bacteria) are specific to either aerobic or anaerobic conditions. Bacteria have a direct role in nutrient cycling and through their oxygen consumption can contribute to an increase in wetland BOD levels. Certain organic and inorganic material can accumulate in the wetland substrate and lead to predominantly oxygen-deficient sediments which generally tend to inhibit decomposition and oxidation reactions. This means that associated metals, oils and nutrients can be tied-up in the sediment for long periods.

When pollutants enter the wetland they are acted upon by biological, chemical and physical processes which interact in a complex fashion. Figure 1.3 illustrates in a simplified form the interactions which occur in a wetland system between the air-water-sediment phases during sequential nitrogen transformations. Plants will take up dissolved inorganic nutrients (ammonia, nitrate, phosphate etc.) and incorporate them into their tissue whilst bacteria and fungi attack the organic material, utilising both carbon compounds and nutrients. The wetland biota die and become detritus in the



After: Kadlec and Knight, 1996

Figure 1.3. Nitrogen Transformation in a Wetland System

basal sediments or may be washed downstream. On an annual basis, pollutants may become buried in the sediments, transformed from one form to another, lost to the atmosphere or washed out of the wetland system either in the original or an altered form.

1.7.2 Pollutant removal processes

In order that the design and operational characteristics of wetland treatment systems are satisfactorily specified, it is necessary to have an understanding of the basic pollution removal mechanisms. Pollutants in urban surface runoff can be removed by wetlands as a result of sediment attachment, degradation, transformation and transfer. They can also be transferred to the atmosphere or groundwater although the latter pathway should be prevented by the use of an impermeable base or liner. The principal physical, chemical and biological removal mechanisms include sedimentation, adsorption, precipitation and dissolution, filtration, bacterial and biochemical interactions, volatilisation and infiltration. Further details on these specific processes are given in Appendix A. Due to the complex interactions between the physical and biochemical processes which occur in wetland systems, these

Table 1.1a. Wetland Pollutant Removal Mechanisms and their Major Controlling Factors

Pollutant Removal Mechanism	Pollutant	Major Controlling Factors
Sedimentation	Solids, BOD/COD, Bacteria/pathogens, Heavy metals, P, Synthetic organics	Low turbulence; Residence time; emergent plants
Adsorption	Heavy metals, Dissolved nutrients, Synthetic organics	Iron and Manganese Oxide particles; high organic carbon; neutral to alkaline pH
Biofiltration and microbial decomposition	BOD/COD, P, Hydrocarbons, Synthetic organics	Filter media; dense herbaceous plants; high plant surface area; organic carbon; dissolved oxygen; microbial populations
Plant uptake and metabolism	P, N, Heavy metals, Hydrocarbons	Large biomass with high plant activity and surface area; extensive root system
Chemical precipitation	Dissolved nutrients, heavy metals	High alkalinity and pH
Ion exchange	Dissolved nutrients	High soil cation exchange capacity e.g clay
Oxidation	COD, Hydrocarbons, Synthetic organics	Aerobic conditions
Photolysis	As oxidation	Good light conditions
Volatilisation and aerosol formation	Volatile hydrocarbons, Synthetic organics	High temperatures and wind speeds
Natural die-off	Bacteria/pathogens	Plant excretion of phytotoxins
Nitrification	NH_3-N	DO > 2 mg/l; Low toxicants; Neutral pH; Temperature > 5-7 degrees C; relevant bacteria
Denitrification	NO_3-N, NO_2-N	Anaerobicity; Low toxicants; Temperature >15 degrees C; relevant bacteria
Reduction	Sulphate (resultant sulphide can precipitate metal sulphides)	Anaerobic (anoxic) zone in substrate; relevant bacteria
Infiltration	Dissolved species (nutrients, heavy metals, synthetic organics)	Permeable base and underlying soils

Table 1.1b. Relative Importance of Wetland Pollutant Removal Mechanisms

Pollutant Removal Mechanism	Pollutant								Description
	Settleable solids	Colloidal solids	BOD	N	P	Heavy metals	Organics	Bacteria, pathogens	
Physical									
Sedimentation	**P**	**S**	**I**	**I**	**I**	**I**	**I**	**I**	Gravitational settling of solids (and adsorbed pollutants).
Filtration	**S**	**S**			**I**	**I**		**I**	Particulate filtered mechanically as water passes through substrate and/or root mass.
Adsorption		**S**				**S**	**S**		Inter-particle attractive forces
Chemical									
Precipitation					**P**	**S**			Formation of co-precipitation with insoluble compounds.
Adsorption				**P**	**P**	**S**	**I**		Adsorption on substrate and plant surfaces.
Decomposition							**P**	**P**	Decomposition or alteration of less stable compounds by UV irradiation, oxidation, reduction etc
Biological									
Bacterial metabolism[a]		**P**	**P**	**P**	**I**		**P**		Removal of colloidal solids and soluble organics by suspended benthic and plant supported bacteria. Bacterial nitrification and denitrification.
Plant metabolism[a]				**S**	**S**	**I**	**S**	**S**	Metabolism of organics and other pollutants by plants. Root excretions may be toxic to certain micro-organisms.
Plant uptake				**S**	**S**	**S**	**S**		Significant quantities of these pollutants will be taken up by the roots.
Natural die-off								**P**	Natural decay of organisms in an unfavourable environment

KEY: **P** = Primary effect; **S** = Secondary effect
I = Incremental effect (an effect occurring incidental to removal of another pollutant)

[a] The term metabolism includes both biosynthesis and catabolic reactions

removal mechanisms are not independent. The considerable variation in wetland characteristics e.g hydrology, biota, substrates etc., means that the dominant removal mechanisms will vary from one wetland to another as well as between differing storm events affecting the same wetland system. These inter- and intra-wetland variations help to explain why wetland pollutant removal efficiencies can vary with respect to both temporal and spatial resolution. Tables 1.1a and b summarise the principal mechanisms that capture, retain and transform various pollutant species found in urban runoff and the controlling factors that promote the various removal mechanisms and which lead to improved water quality.

As noted previously, the large majority of UK urban wetlands are free water surface systems containing emergent macrophytes in which the near-surface water layer is aerobic but with the deeper water and substrate being normally anaerobic. A constructed wetland has been traditionally thought to provide a combined aerobic-anaerobic environment. The anaerobic zone surrounds the root zone and at the same time provides a mini-aerobic zone surrounding the root hairs formed by the oxygen passed down from the stems and/or leaves of the aquatic vegetation and contributing to the degradation of oxygen-consuming substances and to nitrification. Ammonia is also oxidised into nitrate by nitrifying bacteria in aerobic zones (see Figure 1.3) with denitrification converting nitrate to free nitrogen (or nitrous oxide) in the anaerobic bottom layers and substrate by denitrifying bacteria. These processes will occur most rapidly during summer periods when high temperatures stimulate microbial activity. Solids, settleable organics and solid-associated pollutants such as bacteria, metals and oils are very effectively removed by the physical filtration offered by the vegetation which imposes a considerable hydraulic resistance to the incoming flow.

Soluble metals are typically transformed by microbial oxidation and precipitated in the wetland substrate in the form of oxides or sulphates with soluble BOD removed by both attached and suspended microbial growth in the aerobic surface water layers.

1.7.3 Hydraulic retention time and loading_rates

Perhaps the most important factor influencing the treatment mechanism function is hydraulic retention time i.e the average time that stormwater remains in the wetland. This can be expressed as the ratio of the mean wetland volume to mean outflow (or inflow) rate although it must be noted that if short-circuiting (or high summer evapotranspiration) occurs in the wetland, then the effective retention time can significantly differ from the calculated retention time. In addition, it incorrectly assumes that the entire wetland water volume is involved in the flow and that detention time response to variation in influent flow and pollutant characteristics is linear. Wetlands should have a minimum retention time of at least 10 - 15 hours for the design storm event or alternatively retain the

Hydraulic Retention Time (HRT)
The nominal HRT (days) is the volume (LWD) of free water in the wetland divided by the volumetric inflow rate (Q_{in}; m^3/day):

$$HRT = LWD/Q_{in} \quad (\text{or } D/Q_{in})$$

Where L and W are length and width (m); D is free water depth (expressed as: porosity x water depth). Mean retention time can also be determined by undertaking an accurate tracer study.

Porosity (Void Fraction)
Porosity (expressed as a decimal fraction) = Total Void Volume (m^3) / Total Wetland Volume (m^3)
In an SSF wetland, free water volume fractions are typically 20-40% but can vary between 75-95% for a SF wetland system

average annual storm volume for a minimum of 5 - 10 hours to achieve a high level of removal efficiency. When calculating the retention time for a SSF wetland system, the volume of the bed media must also be considered. The retention time of the bed is calculated from the porosity (or void fraction) of the substrate, which represents the fraction of the wetted volume that is occupied by free (drainable) water. The higher the porosity, the greater the retention volume of water per unit volume of media. However, excessive porosity can lead to scour in the bed causing breakdown of the substrate.

> **Hydraulic Loading Rate (HLR)**
> HLR (m/d) is equal to the inflow rate (Q_{in}; m^3/d) divided by the wetland surface area (A_s; m^2):
> $$HLR = Q_i / A_s$$
> It does not imply that the inflow is uniformly distributed over the wetland surface.

The effectiveness of solids settling is directly related to the particle sedimentation time and time is also a crucial variable determining the efficiency of the biochemical processes. Chemically and biologically-mediated processes both have characteristic reaction rates that must be satisfied if optimum treatment is to be achieved. Thus hydraulic loading rates, water depths and duration of flooding become important criteria for the operation of wetland systems and these need to be considered on a site-specific basis in terms of design storm, substrate and vegetation conditions. It has been suggested that a hydraulic loading rate of 0.2 m^3/m^2/day provides for maximum treatment efficiency whilst another study has recommended guidelines of up to $1m^3/m^2$/day (wetland surface area) and a void storage capacity of $50m^3$ and $100m^3$ per impervious hectare respectively for 5mm and 10mm effective runoff volume. These latter hydraulic design parameters have been successfully used in the modular wetland systems developed by the Environment Agency for urban runoff control and treatment within the Lower Severn area.

1.8 Wetland classification

Research and field surveys have identified a number of quite different pollutant pathways, transformations and interception processes in urban wetlands. These processes operate as an inter-active function of inflow conditions (hydrology, hydraulics etc.) and pollutant characteristics (solids and toxic concentrations, organic loads etc.). Based on a consideration of the controlling processes, it is possible to theoretically identify three fundamental types of constructed wetland (Table 1.2).

Type A is essentially configured as a primary settling facility to maximise sedimentation and where solids capture is the operational objective. Type A can be of single or two-stage form with the latter configuration intended to utilise the sediment adsorptive capacity to lock-in and degrade nutrients. Type B is intended to provide a secondary biological treatment for surface runoff that may be low in solids but carrying high levels of organics and soluble pollutants. Type C provides a hybrid tertiary form of treatment for low flow volumes that may be associated with concentrated levels of micro-pollutants such as dissolved metals or pesticides. With the predominantly temperate climatic conditions and variety of soil types encountered in the UK, most urban wetlands will be of Type A and B1 and most frequently comprise a combined hybrid of these two types constructed in an on-line mode.

Table 1.2. A Process-based Classification of Constructed Wetlands

TYPE	DESCRIPTION	SUB-TYPE	SUB-TYPE DESCRIPTION
A	***Regime:*** High storm event discharge and elevated suspended solids levels ***Dominant Treatment Process:*** Physical sedimentation with adsorbed nutrients (together with bacteria and oil/hydrocarbons) being removed with the solids.	A1	*Single stage*: High coarse solids deposition; moderate and dispersed organic deposition. Direct use of sedimented organic carbon for de-nitrification
		A2	*Two-stage*: High coarse solids deposition; moderate to highly concentrated organic loading; requires larger surface area. Macrophytes provide labile carbon for de-nitrification
B	***Regime***: Baseflow or attenuated discharge, low to moderate solids input; high dissolved and colloidal forms of nutrients and organic materials. ***Dominant Treatment Process***: adsorption and biological uptake by macrophyte and sediment biofilms	B1	Simple organic forms
		B2	Complex fine organic forms e.g from swamp drainage, groundwater seepage etc; longer contact times needed for biofilm removal.
C	***Regime***: Baseflow or attenuated flows high in toxic micro-pollutants e.g dissolved metals, hydrocarbons, pesticides. ***Dominant Treatment Process***: adsorption of toxicants on cellulose biomass		High macrophyte biomass as substrate for adsorption of micro-toxicants

2. WETLAND DESIGN

2.1 Introduction

Factors that will determine the selection of the most appropriate design criteria include:

local climate, topography and geology;

traffic loadings (present and future);

road drainage area;

land availability;

cost;

size/extent and type of receiving water body;

water quality classification and objective (including water uses); and

environmental enhancement value.

A constructed wetland system to treat highway runoff should ideally include the following structures:

oil separator and silt trap;

spillage containment;

settlement pond and associated control structures;

constructed wetland and associated control structures;

final settlement tank;

outfall into receiving watercourse; and

access.

The successful design of constructed wetlands for urban surface runoff management requires the adoption of an integrated multi-disciplinary approach as performance criteria are difficult to set given the inherent random fluctuations in discharge and pollution loadings which characterise stormwater runoff. This temporal and spatial variability makes it difficult to define retention time and hydraulic loading and thus general design rules for urban stormwater wetlands have been developed from empirical performance data and using "single-number" techniques such as drainage area ratio. Thus no UK urban stormwater constructed wetlands are alike in every design respect; a feature readily confirmed from site inspections.

Figure 2.1 illustrates a general integrated design approach showing the major linkages and interactions between the various wetland design elements. Consideration of water quality issues at the preliminary planning stage can help to mitigate or prevent stormwater management problems in urban catchments and reduce the magnitude and difficulty of surface water treatment. Hydrological effectiveness reflects the competing (and sometimes conflicting) factors of retention time, inflow characteristics and storage volume and defines the long term percentage of catchment runoff which enters the wetland basin. Hydraulic efficiency is strongly influenced by basin shape and depth; hydraulic structures such as inlets, outlets and berms; and by the type, extent and distribution of wetland vegetation. Wetland plants are adapted to specific wetting and drying cycles which also significantly influence the organic content and nutrient cycling in the basal sediments. A major factor in determining wetland hydro-cycling (and the overall treatment efficiency) is the interaction between catchment hydrology, basin bathymetry and the hydraulic behaviour (and location) of the outlet structure.

Hydrological effectiveness describes the interaction between runoff capture, hydraulic retention time and wetland volume.
Hydraulic efficiency describes the extent to which plug flow conditions are achieved and the proportion of wetland volume utilised during the passage of stormflow through the wetland system.
Treatment efficiency defines the extent to which surface water runoff pollutants are removed within the wetland

2.2 Design Criteria

2.2.1 Return period and retention time

The treatment performance of a constructed wetland results from the combined effect of the hydrological effectiveness and the treatment efficiency. If design criteria were to be adopted for the treatment of maximum expected peak flows and/or loads, the wetland system would need to be extremely large and over-engineered or the outflow water quality standards considerably relaxed. The design criteria also need to make reference to existing or future water quality objectives (WQOs) and take into account the expected dilution capacities of the receiving water. Normally, performance criteria will be based upon a selected design storm (1, 2…..10 years) to be retained (2, 4…….36 hours) and treated by the wetland and a specified critical flow quality level (e.g 5% flow rate, Q_5; 10% flow rate, Q_{10}……Q_{50}) in the receiving water to be protected. The worst pollution potential is likely to occur during summer with runoff from a short duration intense storm event following a dry period. In this case, a maximum pollution load will be mobilised, the highest inflow rates will be experienced and flows in the receiving watercourse will be at a minimum. The selection of the design storm return period and hydraulic retention time (HRT; see Section 1.7.3) determines the maximum flow intended for treatment in the wetland. Flows in excess of this design maximum should be diverted (or by-passed) directly to the receiving water following a preliminary treatment if possible (e.g oil and grit separation), otherwise such high flows are likely to disturb and mobilise the

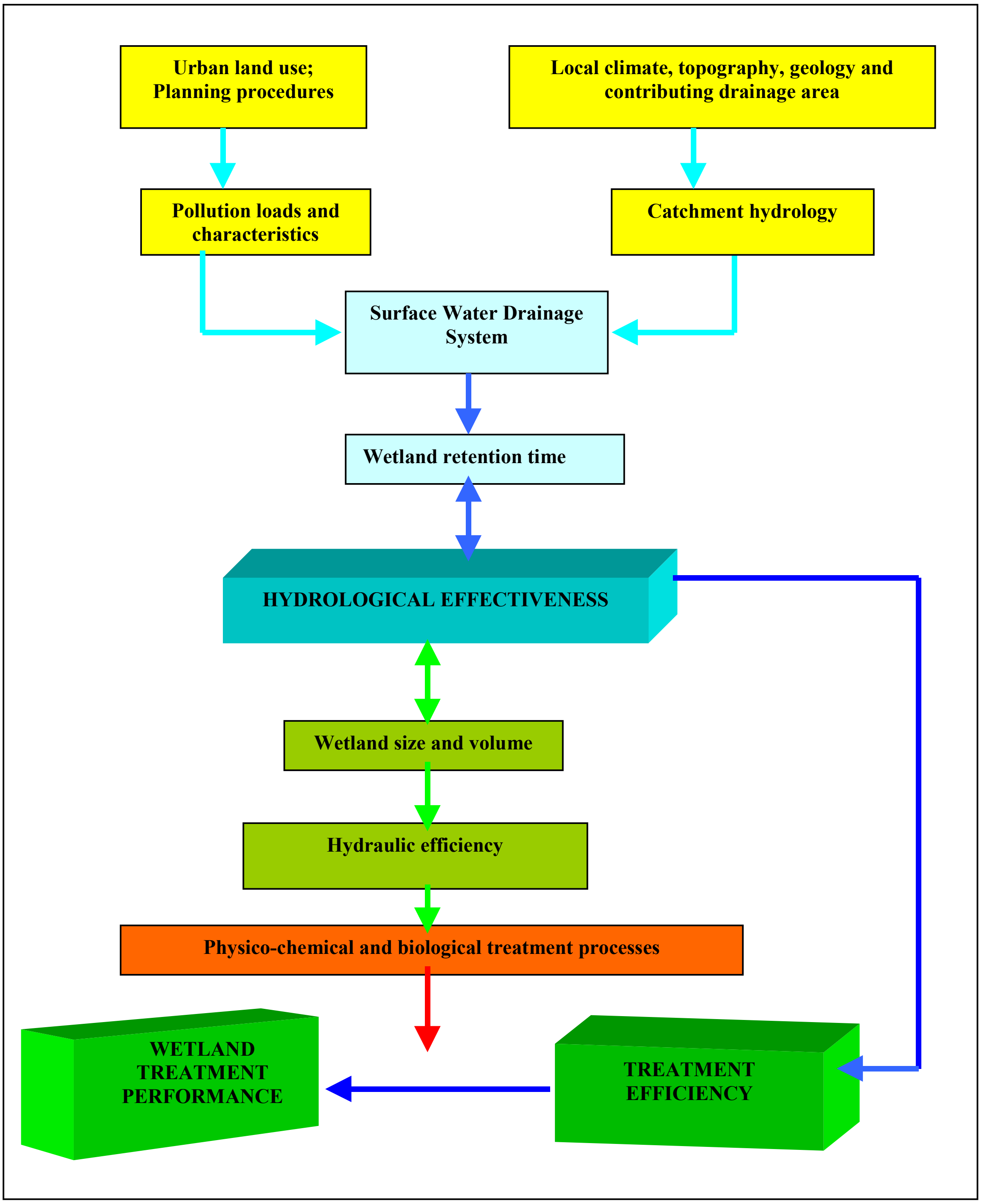


Figure 2.1 Linkages and Interactions between Wetland Design Elements

contaminated substrate as well as damaging the macrophyte vegetation. This is subject to any overall flow restrictions to the watercourse i.e. taking storage into account. The most important criterion for the design of a constructed wetland is the selection of the design storm which in turn determines the wetland size and volume. The objective of the selection process is to determine the critical storm event which will cause the greatest pollution threat, with this storm event being described in terms of its duration, intensity and frequency of occurrence. In this analysis, it is assumed that the selection process will be based upon single rather than multiple event occurrences. Constructed wetlands can be designed to:

- retain short duration storms (e.g less than the 1:1 annual storm event) for the maximum retention time, ensuring that the high flows can be accommodated by the constructed wetland without overland flow in the case of SSF systems or short-circuiting in the case of SF systems. For example, a wetland basin sized to capture 90% of the average annual runoff with a 24 hour drawdown would be likely to overflow between 3 to 8 times per year. This would suggest that a feasible design storm for water quality control purposes might be in the order of a two to four month storm event.
- retain longer duration storms ensuring that the initial first flush volume (equivalent to 10 - 15 mm effective rainfall runoff) containing the heaviest pollution loads receives adequate treatment. It is important that the constructed wetland is large enough to capture the first flush of the larger storm events to achieve such partial treatment and to delay outflow discharges to the watercourse until natural dilution flows have risen.

Where the availability of land and finance is not problematic, the constructed wetland should be designed to treat storms with a return period of 10 years, although the design of attenuation could be up to the 100 year return period. If a compromise is necessary requiring a design based on a shorter return period, the system should be capable of treating the polluted first flush of any storm event. Retention time is an extremely important factor in the treatment performance of treatment by constructed wetlands and even a minimum retention time of only 30 minutes will help to remove the coarse sediment fractions. Considerations affecting the retention time include the aspect ratio (width : length), the vegetation, substrate porosity and hence hydraulic conductivity, depth of water, and the slope of the bed. Water level and flow control structures, for example flumes and weirs are also required to keep the hydraulic regime within desired parameters. An "ideal" retention time is dependent on the pollutant removal processes operating in the wetland system. Solids sedimentation can be achieved relatively quickly and a 3 - 5 hour retention will remove a substantial proportion of the coarse solids. However, in order to achieve removal of degradable organics, bacteria and other toxic species associated with the finer solids fractions, much longer retention periods of at least 24 hours will be required (Halcrow & Middlesex University, 1998). When calculating the retention time in a SSF constructed wetland system, the volume of the bed media must also be taken into account (see Section 1.7.3).

2.2.2 Wetland sizing

Empirical Approaches

The principal problem of wetland design for the treatment of urban and highway runoff is that of optimum sizing given the episodic and random nature of discharge occurrence and the possibility of a rapid succession of inflow events. Sizing is crucial in controlling both the hydraulic loading and retention times needed to give maximum contact and biofiltration/uptake opportunities. The pollutant removal efficiency of an urban stormwater wetland will be directly affected by the frequency, spacing and duration of storm events, all of which are extremely difficult to pre-define. This explains why empirical approaches to the sizing of urban wetlands have been widely adopted. The utility and appeal of such approaches lies in their ability to provide a rapid and robust initial screening methodology for potential wetland alternatives at the early design stages but considerable caution must be exercised in extending them to final design (Kadlec, 2000).

One such approach is to consider the relative percentage of the contributing catchment area or connected impervious area and typically figures of between 1% to 5% have been suggested (Ellis, 1999) for this wetland/watershed area ratio (WWAR). Assuming a 2% - 3% WWAR value, for a 10 hectare development site and with retention times equal to 4 - 6 times the mean storm runoff volume:

Surface area = 100,000m^2 x 2/100 = 2000m^2
Retention volume = 10ha x 100m^3/ha = 1000m^3
Average wetland depth = 1000 (m^3) / 2000 (m^2) = 0.5m
(see Section 1.7.3 and/or Fig 2.2)

Such sizing criteria would pose considerable land-take difficulties and in any case does not account for any performance considerations.

Nevertheless, Kadlec and Knight (1996) have shown that such an approach derives hydraulic loading rates (HLR) which are equivalent to the range of HLR values quoted in the national US database (NADB) For point-source SF treatment wetlands.

Wetland Sizing and HLR

As an illustrative example, given an average annual rainfall of 625mm and a runoff coefficient (Rc) of 65%:
average annual daily rainfall rate = 625 /365 = 1.71 mm/d
and total runoff = 1.71 x 0.65 = 1.11 mm/d (= Q_{av})
For a 4% contributing WWAR ratio (A_s = 1/25), the average annual wetland hydraulic loading rate (HLR = Q /A) will be:
1.11 x 25 = 27.75 mm/d
and sizing of the wetland basin can be based on this expected loading value. This calculation yields a high final HLR value but is based on a high Rc value and WWAR ratio.

Where the wetland system is intended only to provide a sedimentation facility in terms of solids and solid-associated pollutant removal, the system can be designed to retain a volume equal to the catchment design treatment volume derived from Figure 2.2 . However, where it is expected that the wetland will provide a secondary biological treatment to remove organics and other biodegradable pollutants or nutrients, the minimum permanent pool volume should be increased to 2 to 3 times the volumes noted in Figure 2.2 to allow for the increased amount of aquatic vegetation.

Inspection of Figure 2.2 might indicate that the most cost-effective stormwater storage volumes for water quality treatment could lie between 50 - 75 m^3/ha for most residential and commercial/industrial catchments in the SE England region. A wetland sized to capture such volumes will also retain the first-flush of larger storms. Oversizing the wetland basin will only result in the more frequent events (which carry most of the total annual pollution load), receiving less treatment and thus providing a poorer overall removal efficiency.

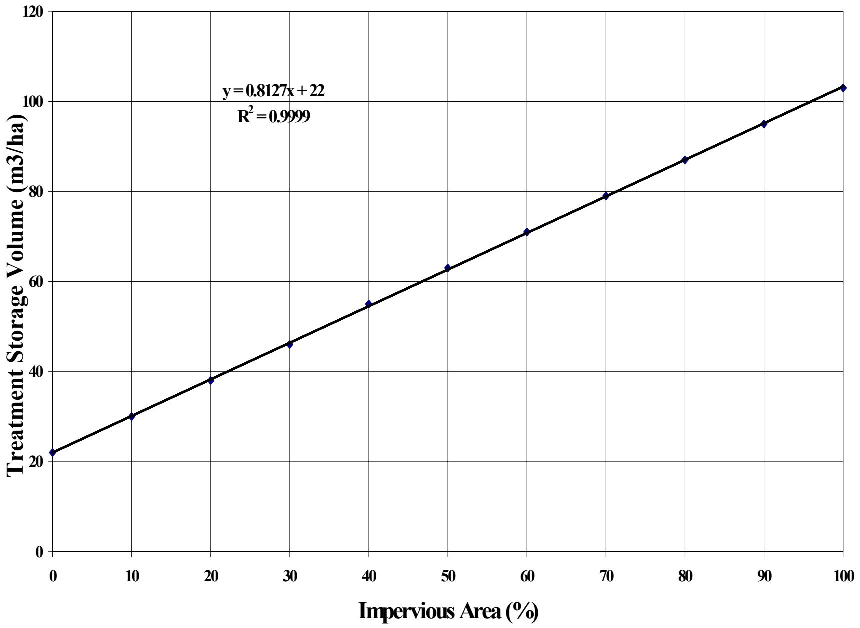


Figure 2.2 Wetland Treatment Storage Volumes

In addition to the design storm and retention time, the following criteria are also recommended for horizontal subsurface flow wetlands:

Aspect ratio (Width: Length)	:	1:4
Slope of Wetland Bed	:	0.5 - 1%
Minimum substrate bed depth	:	0.6m
Hydraulic conductivity of substrate	:	10^{-3} m/s to 10^{-2} m/s

Once the design storm and retention time choice has been made, the size of the conceptual constructed wetland can be calculated using Darcy's Law and the above criteria as: Average daily flow rate (Q_d; m^3/s) = Ac. k_h ($\partial H/\partial x$)
where Ac is the cross-sectional area of the bed, k_h is the hydraulic conductivity of the substrate (m/s) and ($\partial H/\partial x$) is the slope or hydraulic gradient of the bed (m/m). Darcy's Law assumes laminar uniform and constant flow in the media bed and clean water. In a SF wetland, flow will be channelled and short-circuited and the media will be covered with biological growths and therefore the equation only has limited usefulness in such wetland design. Nevertheless Darcy's Law does provide a reasonable approximation of flow conditions in SSF constructed wetland beds if moderate sized gravel (eg 10mm pea gravel) is used for the support medium. Figure 2.3 provides a schematic section through a SSF constructed wetland illustrating some of these design criteria.

Hydraulic Conductivity (k_h)

Is the coefficient of permeability representing the rate at which water moves through the porous media and can be determined directly from field tests or estimated for clean, un-rooted media as: $k_h = 12{,}600\ Dp^{1.9}$
where Dp is the diameter of the substrate media. 8 - 12mm gravels typically have a k_h value of 270 m/d with silts (0.005 - 0.05mm) having a value about 0.08 mm/d.
Siltation and algal/biomass accumulation will reduce the k_h value especially close to the wetland inlet by some 10% or so.

2.2.3 Optimal hydraulic loading

During storm events, high rates of stormwater runoff may discharge onto constructed wetlands, but optimal hydraulic loading rates (HLR; see Section 1.7.3) should not exceed $1m^3/m^2/d$ in order to achieve a satisfactory treatment. It has been suggested that an arbitrary HLR breakline appears to be about 2.7 ha catchment area/1000 m^3 storage volume/day, with wetlands having a large area per flow unit (a lower loading rate) being normally SF systems and smaller areas (with higher loadings) associated with SSF systems.

2.2.4 Flow velocity

Flow velocity should not exceed 0.3 to 0.5m/s at the inlet zone if effective sedimentation is to be achieved. At velocities greater than 0.7m/s, high flow may damage the plants physically and cause a decline in system efficiency. Appendix A shows how expected maximum inflow velocity can be determined from consideration of design peak flow rate (Q_{pkmax}) and wetland area (A).

2.2.5 Inlet

The inlet pipe should be constructed in such a way that influent flow is evenly distributed across the width of the bed. This may be achieved using slotted inlet pipes or a notched gutter (slots should be large enough to prevent clogging by algae). The distribution system must be designed to allow maintenance in case of blockage. Riser pipe distributors have been adopted on many wastewater treatment systems (Cooper *et al.*, 1996). A level spreader device (serrated weir plate, hard aprons etc.,) can give uniform gravity-fed distribution systems especially if they spread the influent flow across a fully-maintained grassed filter strip prior to entry into the wetland cell.

Some type of stilling structure under the inlet, usually a 1m wide stone trench (rip-rap or gabion zone), is necessary to either dissipate high water flows, or contain the inlet distributor pipe. Rip-rap and gabions are blankets of stones placed to protect erosion zones. The stones for rip-rap are laid directly on the bed, whereas they are packed in cages for gabions.

2.2.6 Substrate slope

The longitudinal slope of the substrate bed parallel to the flow path, should not be less than 1%. The surface of the substrate should be level (see Figure 2.3).

2.2.7 Outlet

The level at which the outlet is set is determined by the lowest water level required in the constructed wetland. Until further information is available, it is considered that the lowest level in the wetland should be 300mm below the substrate surface dependent on plant type (see Section 2.4). An additional source of water may be needed to supply the reedbeds during dry periods.

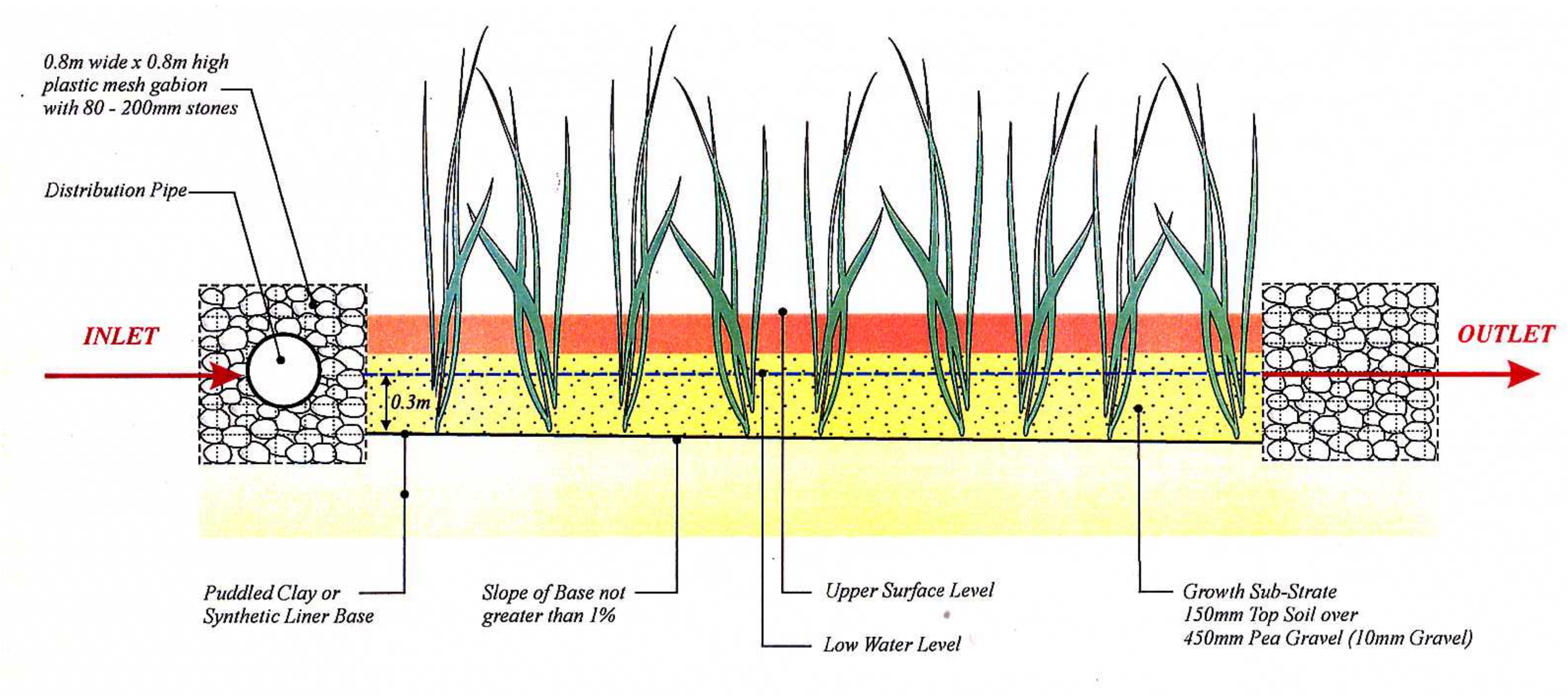


Figure 2.3 Section Through SubSurface Constructed Wetland

Ideally the outlet structure should incorporate control measures which allows the water level in the bed to be varied; a flexible plastic pipe linked to a chain is an appropriate low cost option (Cooper *et al*., 1996). The control should at least incorporate a measure to allow periodic raising of water level for weed control and bed oxidation. A recent 2001 HR Wallingford R&D project "*Guide for the Drainage of Development Sites*" Report SR574 on surface water runoff management commissioned by the DETR, has indicated that temporary storage may not be particularly effective in providing sufficient downstream flood protection for extreme events. One strong recommendation is for permanent storage with long release times, and this requirement can be satisfied by wetland basins fitted with adjustable outlet controls to maintain outflow rates and volumes compatible with a sustainable receiving water regime.

At the outlet zone it is recommended that an additional rip-rap (or gabion) zone be inserted to prevent weed growth and resuspension of reedbed substrates (Figure 2.3). Outlet structures are particularly prone to debris accumulation and a gabion zone (or debris screen/fence) will help to alleviate this problem. If high flood conditions at the site are anticipated, there should be appropriate provision such as emergency overflow spillways or by-passes, to facilitate through-flow and prevent disturbance and flushing of the wetland substrates.

2.2.8 Aspect ratio

An aspect ratio (length: width) of 4:1 for SSF wetlands and 10:1 or higher for SF wetlands has been recommended for domestic wastewater treatment wetlands. However, the IWA (2000) technical report considers that any aspect ratio with a good inlet distribution can be applied, as previous assumptions that wetlands with high aspect ratios would function more efficiently and be closer to plug flow have not been confirmed from tracer studies. Problems of short-circuiting can be minimised by careful construction, intermediate open-water zones for flow distribution and use of baffles and islands.

2.2.9 Aeration

A grid of slotted plastic pipes (say diameter of 100mm) should be installed vertically in the substrate (100mm protruding above the surface, and penetrating the full depth of the substrate) at 5m centres, to serve as static ventilation tubes and aid aeration of the root zone.

2.2.10 Bird deterrent

Plastic poles should be erected to support lines of bunting to discourage birds from feeding on young plants. The height of the bunting should be about 1.5m above the substrate surface.

2.2.11 Non-metallic items

Non-metallic items should be incorporated into the construction of the wetland so that metals in the wetland only come from stormwater runoff. Therefore gabions should be encased with geotextiles and the poles supporting bunting should be plastic.

2.3 Substrate Structure

Horizontal surface flow (SF) wetlands utilise a natural soil substrate to provide organics and nutrients to maintain plant growth, whereas subsurface flow (SSF) wetland substrates should primarily provide a good hydraulic conductivity. Nutrient supply can be supplemented to the subsurface flow if required. The following sections primarily address the subsurface structure of SSF wetlands.

A combination of organic and clay based soils, sand, gravels and stones are used in SSF constructed wetlands to provide support for plants, reactive surfaces for complexing of ions and other compounds and attachment surfaces for microbes which directly or indirectly utilise pollutants. The type of substrate used will have an effect on the hydraulic conductivity and efficiency of the constructed wetland and must allow for a sufficiently high hydraulic conductivity to enable wastewater to flow at a sufficient rate for treatment without backing up and causing overland flow.

Although wetland plants will grow optimally in deep rich soils which allow for extensive root and rhizome penetration, gravels are also needed to increase total hydraulic conductivity, provide a matrix for supporting plant roots and act as a silt trap during storm events. Nutrient-poor substrates should not be rejected as slow-release fertiliser pellets can be added. Studies have suggested that substrate type is irrelevant to plant growth once the plants have become established.

Nutrient-poor peat based organic soils are best avoided due to their acidic nature and lack of support for emergent macrophytes, and hence the need for additional anchoring devices. Nutrient-poor clays and gravels on the other hand may be too compact for root penetration, or be impermeable to water required by roots. Clay soils may be more effective in adsorbing certain pollutants owing to their high cation exchange capacity, but should be used with care since changes in pH have been shown to release adsorbed pollutants. The texture of sandy soils allows for cost-effective planting by hand. Sands and gravels with low capillarity may require irrigation if drying out of roots is to be avoided during times of low influent discharge.

Gravel provides the most suitable substrate for SSF constructed wetland emergent plants, supporting adequate root growth, high conductivity and superior permeability. Ideally, prior to use, all components of a substrate mixture should be analysed for hydraulic conductivity, buffering capacity, pH, plant nutrient levels and microbial activity. Hydraulic conductivity is one of the most important determinants in pollutant removal efficiency, and is especially important in SSF constructed wetland systems where purification processes are largely confined to the root zone.

A sufficient rooting depth is also required to prevent physical damage of plants by high velocity stormflows and freezing. A 0.6m depth of washed pea gravel (10mm sized gravel) is appropriate and is similar to the 0.6m depth of root penetration possessed by the deep rooting *Phragmites*. Coarse organic top soil may be mixed with the gravel in a maximum ratio of 1:4 to provide a nutrient source and to enhance metal removal during the plant establishment phase. However, its addition will reduce the hydraulic conductivity of the substrate. Water depth and substrate depth are the most important determinants of retention time in SF systems and SSF systems, respectively. Factors determining the depth of substrate for a SSF system include cost of substrate, depth of root penetration, retention time and climate. Substrate temperatures in excess of 3-5°C must be maintained in order for sulphate-reduction processes to proceed. In colder climates substrate depth may be increased to maintain adequate temperatures.

Natural clay, bentonite, geotextile or plastic (high or low duty polyethylene) liners may be used as reedbed bases, in instances where prevention of leakage to groundwaters is imperative. An impermeable liner is also necessary to retain water in the wetland during dry periods. A required depth of at least 0.6m is required to contain the penetration of plant roots and rhizomes *(Typha latifolia:* 0.3m; *Phragmites:* 0.6m), and prevent leakage of pollutants to groundwater. The top surface of the substrate must be level. This allows flooding of the reedbed to occur for control of weed growth when the reeds are being established.

2.4 Planting Considerations

Constructed wetlands have traditionally utilised plant species commonly occurring in water bodies and watercourses, which were known to thrive in nutrient-rich situations and were generally pollutant tolerant. The main plant species utilised in sewage wastewater treatment has been the common reed (*Phragmites australis*), which led to the systems being known as reedbed treatment systems. Reedmace (*Typha latifolia* and *Typha angustifolia*) has been increasingly used, both in sewage-derived wastewater treatment and particularly in the treatment of surface runoff and industrial effluents. Other plant species have played a lesser role in wastewater treatment, such as flag iris (*Iris pseudacorus*), bulrush (*Schoenoplectus* spp.) and sedges (*Carex* spp.).

It is recommended that vegetation for stormwater wetland treatment systems should be selected using the following criteria:

- a rapid and relatively constant growth rate
- high biomass, root density and depth
- ease of propagation
- capacity to absorb or transform pollutants
- tolerance of eutrophic conditions
- ease of harvesting and potential of using harvested material
- growth form (visual appearance)
- ecological value
- local retail (or nursery) availability

A list of the most commonly utilised emergent/semi-aquatic and true aquatic plant species is given in Table 2.1. It is recommended that a horizontal SF or SSF constructed wetland is planted with one or both of two main species. Reedmace

Table 2.1 Plant Species Commonly Used in Constructed Wetlands

Scientific Name	Vernacular Name
Emergent Species	
Acorus calamus	Sweet-flag
Butomus umbellatus	Flowering rush
Carex spp.	Sedge species
Iris pseudacorus	Yellow iris
Juncus spp.	Rush species
Phalaris arundinacea	Reed canary grass
Phragmites australis	Common reed
Sagittarius spp.	Arrowhead species
Schoenoplectus spp.	Clubrush species
Typha latifolia	Common reedmace
Aquatic Species	
Lemna spp	Duckweed species
Myriophyllum spp.	Water milfoil species
Ranunculus flammula.	Lesser spearwort

(*Typha latifolia*) is shallow rooting and requires the water level to be maintained at or up to 100mm above the surface of the substrate; and also common reed (*Phragmites australis*) which is more tolerant of variation in the water level; and a fringe of other plants such as Iris, to soften the wetland appearance. The suitability of *Typha* for treating metal-contaminated waters is well known, but a recent study of *Phragmites* has shown that it accumulates zinc in its aerial sections more efficiently than *Typha* (Bateman *et al.,* in press). The use of a range of emergent and floating aquatic plants is recommended to enhance the ecological and visual interest and should be drawn from Table 2.1.

In constructed wetlands the required vegetation can, in theory, be established from either direct seeding into the growing media, seedling planting, root cuttings, leaf or shoot cuttings or whole plant translocation. However, experience from existing systems reveals that rhizome cuttings of *Phragmites* and *Typha* in particular have been most successful, along with pot grown seedlings. Plants can be obtained from existing wetlands with prior authorisation or from retailers. A retailer with experience of constructed wetland planting is recommended as pollution tolerant genotypes and a planting service may be available. Information on planting can be obtained from Merritt (1994) and Cooper *et al*., (1996). A summary of the main methods used to establish common reed is given in Table 2.2. Less information is available on establishing other species of emergent plants, but it is considered likely that most of the techniques developed for establishing reeds would be applicable to other rhizomatous species (Merritt, 1994).

Attention needs to be paid to water levels throughout the first growing season as young plants can be killed off by even shallow flooding. Nutrients may be a limiting factor of initial plant growth in urban and highway runoff treatment wetlands and a supplementary source of nutrients from slow release pellets may be required. Long term maintenance of water levels is also important to prevent stress on the plants, especially *Typha*. At sites which attract large numbers of waterfowl, netting should be used to protect the youngest shoots from grazing. Older reeds require at least the top one-third to be protruding above the water level (Merritt, 1994). Annual inspections of both the pre-settlement pond and the final settlement tank should be made to determine if sediment removal is required. If significant growths of algae are present, they should be removed and cylindrical bales of barley straw wrapped in hessian should be introduced to prevent further algal growths.

Table 2.2 Summary of the Main Methods Used to Establish the Common Reed (*Phragmites australis*). (After Merritt, 1994)

Reed Source	Optimal Timing	Advantages	Disadvantages	Notes
Seeds	April- May	Easy to handle	1) Low seed viability 2) Very precise water levels required 3) Few commercial sources	Spread seed (20 - 125/m^2) on bare wet soil. 5 - 6 weeks after germination, flood to depth of 20mm, then gradually raise water as plants develop, to kill off terrestrial plants.
Pot grown plants	April-May (after frosts)	Easy to handle	1) High capital outlay 2) Intolerant of flooding 3) Few commercial sources	Plants in wet soil (4 plants/m^2) can produce fairly dense growth within first year. Gradually raise water levels as plants develop.
Stem cuttings	May-June	1) Easy to collect from managed reedbed 2) Easy to handle	1) Potential disturbance to source reedbed 2) Requires rapid transfer from donor site	Take 600mm apical cuttings from growing plants. Plant in shallow water. 10 - 15 stems/m^2 can give a good level of cover within first year.
Mature plants	Not known	1) Tolerant of fluctuating water levels 2) Timing more flexible	Requires heavy machinery for digging up and planting	Ensure roots are removed cleanly and planted to an appropriate depth.
Rhizome cuttings	Feb-April	Can be undertaken outside bird nesting season	1) Reasonable critical water level control 2) Difficult to collect	Cuttings should include 1 or 2 nodes. Plant in c. 40mm of damp soil with part of rhizome exposed. Flood gradually after shoots emerge.
Soil containing rhizomes	Feb-April	1) Can be undertaken outside bird nesting season 2) Soil may introduce associated invertebrate community 3) Collection is quick and does not require any specialist knowledge	1) May require extra excavation to accommodate added soil 2) Moving and planting require heavy machinery 3) Bulk results in high transport costs 4) Soil may introduce unwanted plants 5) Viability uncertain; only some rhizomes will be correctly aligned	Spread at least 0.25m depth of rhizome-containing soil across the required area. keep moist, but not flooded until shoots emerge. Then gradually raise water levels.

2.5 Pre and Post Treatment Structures

2.5.1 Oil separator, silt trap/infiltration trench and spillage containment

Traditional pollution control measures for urban and highway stormwater runoff in the UK have included grit and oil separators for the reduction of sediments and hydrocarbons. They are, however, inefficient in removing the majority of the pollution load and the finer and more mobile sediments and solid-associated pollutants including oil (which clog some designs of constructed wetland treating road runoff). Integrated pollution control systems including a combination of oil separators, silt traps/infiltration trenches, spillage containment facilities and wetland-forebays or lagoons, located prior to the constructed wetland cell(s), can provide for pre-treatment of raw stormwater runoff and help to prevent siltation in wetland inlet zones (Figure 2.4).

Oil and phytotoxic chemicals in urban and highway runoff can seriously affect the treatment efficiencies of constructed wetlands and the viability or performance of the plants. As constructed wetlands require 1-3 years to mature and become capable of efficient wastewater treatment, bypass oil separators, silt traps and/or infiltration trenches and spillage containment facilities must be installed prior to the discharge of runoff into the constructed wetland. All these structures must be tamper-proof and easily accessed. The spillage containment facility should have a minimum volume of 25 m^3. Whilst the provision of a front-end, pre-treatment sedimentation trap or lagoon may be an efficient engineering structure to take out litter, coarse grit and other solid-associated pollutants such as oil, such drop structures represent a trap for small amphibians, reptiles and other wildlife which may be funnelled through the sump during rainfall events.

Where SuDS retrofitting is being considered to a conventional kerb-gutter-gulley system, it might be feasible to consider the use of a hydrodynamic separator with the flow-through supernatant effluent passing on to a lined stone infiltration trench or distributed over a grass filter strip and/or swale before discharging to a wetland system for final treatment. This form of pre-treatment has been adopted on part of the A5 Shrewsbury Bypass where road surface runoff passes from conventional fin drains to a separator, swale and wetland treatment-train system.. The basal contaminated sediments in the separator are discharged directly to the foul system.

Where land availability is not limited (ie. rural and semi-rural areas), forebays with additional oil booms on the water surface, have been advocated to serve as secondary sedimentation chambers to reduce the initial flush of pollutants into the main wetland (CIRIA, 1993). Such forebays can be readily constructed by inserting a submerged dam of crushed rock supported by rock gabions across the inlet zone or by constructing a diversion weir in the inflow channel to direct first-flush volumes to an off-line settlement pond. The incorporation of pre-settlement ponds if space is not limited is also recommended.

2.5.2 Pre-settlement pond

A review of a number of studies in the US and Europe, suggested that maximum pollutant removal can be achieved in a pre-settlement pond which is equivalent to some 10 - 15% of the total wetland cell volume. The EA Midlands Region urban constructed wetlands utilise a stilling pond and sedimentation trap of 10 m^3 capacity to capture influent stormwater debris/litter, grit and oiled sediment. This front-end basin can also serve as a back-up spillage containment facility (Figure 2.4).

2.5.3 Final settlement tank

If sufficient land is available, a final settlement tank (concrete structure) with a minimum capacity of 50 m^3 extending across the width of the wetland can be installed (Figure 2.4). The tank will help prevent fine sediment from the wetland being transferred into the receiving water body. The final settlement tank is an idealised part of the overall system and only needs to be included in the overall design where greatest protection to sensitive receiving waters is required. Regular

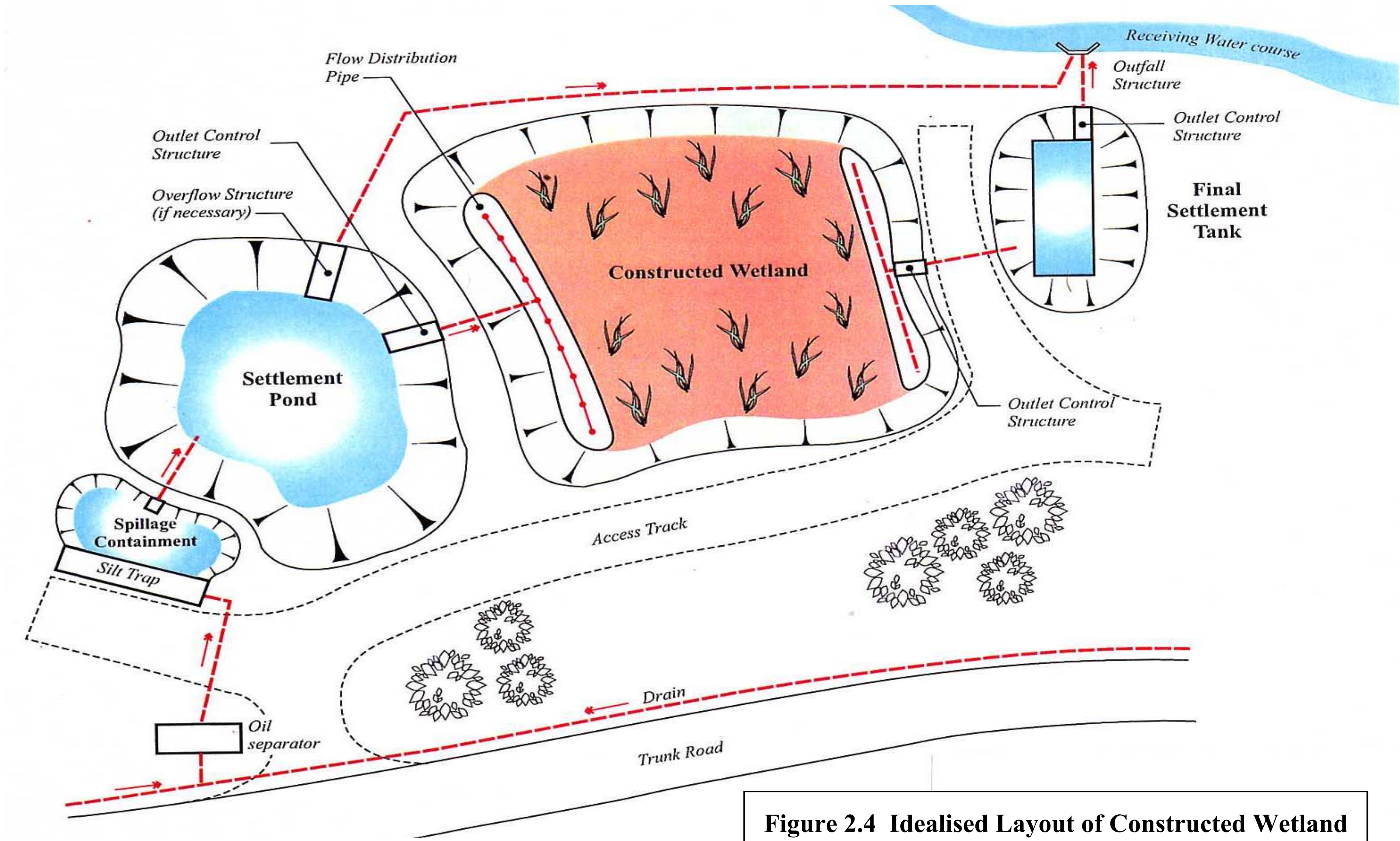


Figure 2.4 Idealised Layout of Constructed Wetland

maintenance is recommended to prevent collected sediments being resuspended during high flows. The rate of sediment deposition will vary with each catchment so the frequency of sediment removal cannot be predicted. Annual inspections should be made to determine if sediment removal is required.

2.6 Wetland Retrofitting

2.6.1 Basic principles

Retrofitting means the installation of a treatment system into a structure that already exists. The physical attenuation of storm runoff from urban developments and highways has been practised for many years and there are many such flood balancing facilities, for example, adjacent to highways and downstream of urban areas throughout the UK. Although these traditional facilities generally do not include vegetative systems, some have been naturally colonised by aquatic plants including reeds (see Section 1.3). To provide a quality treatment, in addition to their existing flood attenuation capabilities, it may be possible to retrofit a constructed wetland into these structures. Such retrofitting can be done into either an existing wet detention (with permanent pool) or dry retention storage basin although in both cases prior consideration must be given to the potential loss of storage volume due to the introduction of the aquatic vegetation and substrate. Nevertheless, retrofitting detention basins to meet more than one discharge criterion can provide beneficial water quality and habitat outcomes without compromising the prime drainage and flood protection requirements.

Given apparent changes in climate in the UK, with the increased risk of more frequent summer storms and prolonged periods of winter rainfall, it is now generally accepted that the introduction of SuDS structures into existing development is likely to have an important future role to play in the prevention of flooding and pollution of low lying urban areas. The revised (February 2001) DETR (now DEFRA) planning guidance for local authorities and developers, Planning & Policy Guideline (PPG) Note 25 "*Development and Flood Risk*", includes reference to the use of sustainable drainage measures. Nevertheless, the same weather conditions render the safe design of such SuDS even more problematical. Such wetland SuDS retrofitting into existing urban development should not therefore be undertaken lightly and requires careful design in collaboration with local residents, their elected representatives and planning authorities, the regulatory agencies, local land owners and the various private and public agencies having a vested interest. In particular, safety (whether real or perceived), post-project liability and maintenance are likely to be considerable constraints.

When considering whether to retrofit subsurface flow (SSF) constructed wetlands into existing urban balancing ponds, the following issues need to be examined:

- does suitable access exist or can it be provided?
- can the storage for flood attenuation be safely reduced (at all or enough) so that the 0.6m deep substrate of a constructed wetland can be incorporated?
- is the outlet structure of the balancing pond offset from the inlet structure? If the outlet is offset (ie not directly opposite the inlet) then the flow could short-circuit. Short-circuiting could be reduced by inserting plastic baffles into the

substrate to increase flow path length or introducing islands to direct water flows and reduce "dead" zones as well as helping oxygenation (CIRIA, 1993).
- does the balancing pond have an impermeable liner? An impermeable lining is necessary to retain a minimum water depth to sustain the plants during periods of no rainfall.

It is anticipated that a constructed wetland retro-fitted into an urban stormwater balancing pond will operate as follows:
- initially, as storm flows arrive, the flow will pass through the substrate and therefore subsurface flow treatment will occur.
- if the storm flows continue until the water level in the pond rises above the surface of the substrate, then the constructed wetland will operate as a surface flow system.

An emergent vegetation/open water ratio of about 30:70 should be maintained as a minimum in order to sustain ecological utilisation. This ratio is the minimum threshold for a range of waterfowl and wetland bird species such as mallard, moorhen, coot etc (CIRIA, 1993). The wetland development close to the inlet and adjacent fringe will not only be ecologically valuable, but will also enhance metal, hydrocarbon and nutrient removal as well as help conceal unaesthetic changes in water level.

2.6.2 Retrofitting flood storage ponds

A schematic example of a constructed wetland retrofitted into a balancing pond is given in Figures 2.5, 2.6 and 2.7. That retrofitting of wetlands into existing storage basins can provide opportunities for extending and integrating a range of environmental benefits into SuDS approaches can be illustrated by reference to the flood storage facility located at North Weald Bassett, Essex. An original off-line 38,000m^3 dry retention basin was constructed here in 1991/1992 to divert flood flows on the North Weald Brook up to the 1:50 storm event which were generated by upstream stormwater runoff from 350ha of agricultural and residential land use. A 0.5 km box culvert diverted wet weather flows to a 2ha dry storage basin which provided a drawdown time of 24 hours for the design storm event. The estimated total cost of the original scheme was £1.25M including cost of fees, land purchase and compensation payments. The consultant's report considered that the 1:50 year compensatory flood storage facility provided benefits of nearly £2.5M based on assessed damage to downstream commercial and residential property in North Weald Bassett. The discounted protection benefits excluded any

The Wharrage Wetlands, Redditch

A series of retrofitted facilities has been built by the Environment Agency Midlands Region into the existing flood plain of the Wixon Brook to store and treat contaminated storm runoff from a 4 km^2 urbanised catchment within which 65% is occupied by residential, industrial and highway surfaces. The retrofitted system utilises pools and cut-off meanders to construct storage ponds and reed beds. The wetland train consists of a 0.198ha upper silt and oil trap, a 0.369ha middle flow and quality balancing pond with marginal planting, and a final 0.214ha stabilisation and treatment (*Phragmites*) reed bed; a total 3,500 m^3 storage and treatment facility being provided. The excavated silt and spoil has been used to landscape the adjacent river corridor to provide valuable ecological micro-habitats for wildlife and amenity development including the construction of an artificial badger sett.

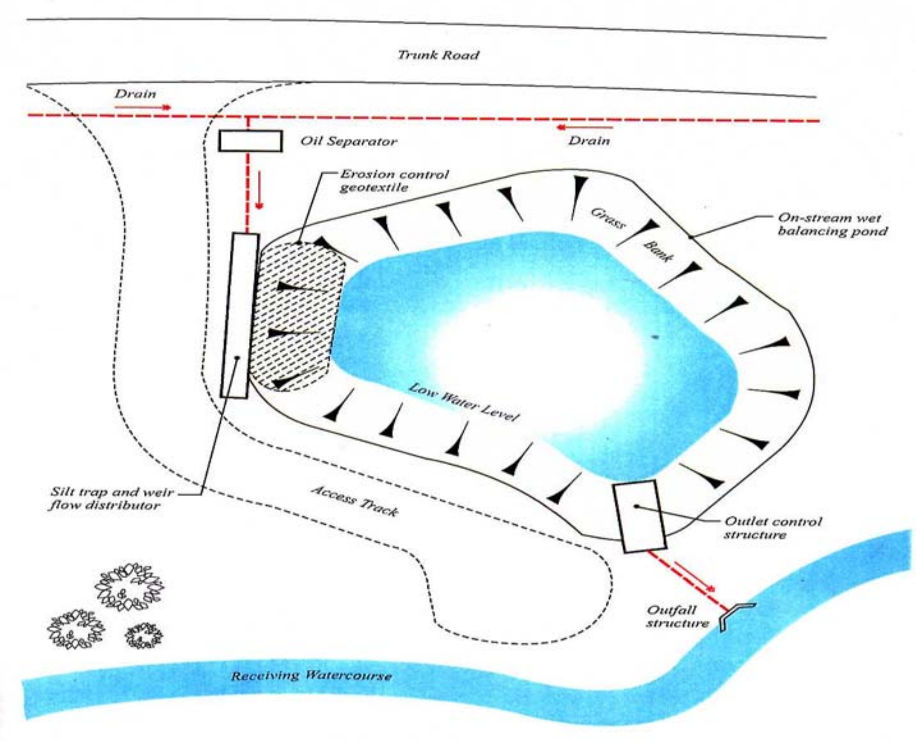


Figure 2.5 Original On-Stream Wet Retention Balancing Pond Before Retrofitting

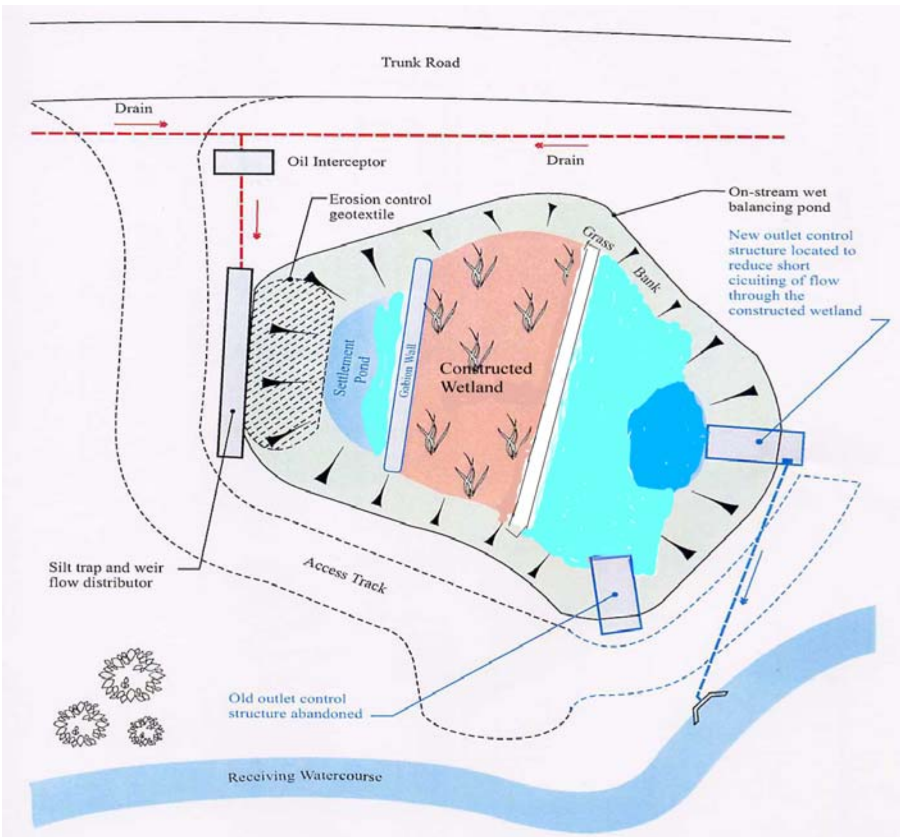


Figure 2.6 Flood Balancing Pond Following Retrofitting to Incorporate a Constructed Wetland

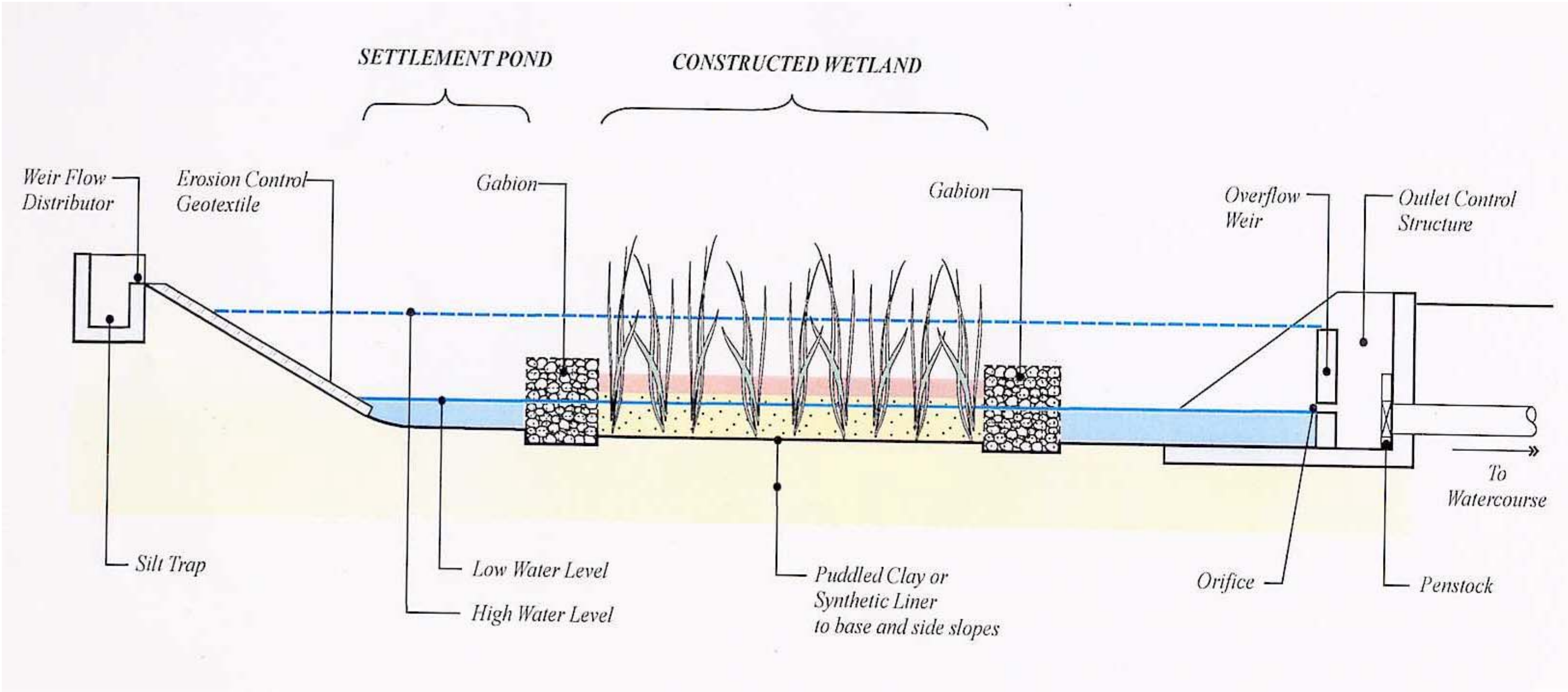


Figure 2.7 Section Through Retrofitted Constructed Wetland

consideration of traffic disruption, damage to roads, public utilities/services or costs of emergency services. Thus the total benefit figures (benefit-cost ratio of nearly 3:1), were well in excess of the capital costs of the flood diversion and storage scheme. The scheme was completed in 1991/1992 with the extended wetland facility being retrofitted by Epping Forest District Council into the dry flood storage basin during 1995/1996 essentially as a community amenity and educational feature. Spoil from the wetland excavation was used to build a small island as a wildlife refuge and to construct embayments on the southern margins of the basin with *Typha*, *Phragmites* and *Scirpus* species being planted to form the wetland vegetation. No consideration was given in this retrofit design to a water quality treatment function for the wetland although it may provide such a further secondary benefit. The original dry balancing basin was already fitted with a sediment trap at the inlet to contain coarse solids and debris prior to discharge into the open basin.

One retrofitting approach to convert a conventional flood storage basin would be to insert dual outlets to match separate discharge criteria. The first high-level outlet is sized to attenuate the peak design flood event (1:10, 1: 25 or 1:50 etc.) and represents the original design criteria. The second (low flow) outlet might be selected to attenuate the 0.3 RI to 1.0 RI storm events by the use of riser orifices set into the wall of a flow inlet pit or a riser pipe (Figure 4.4). Above the 1.0 RI event, overflow of the inlet pipe or riser allows the full design storage capacity of the outlet pipe to be utilised. This arrangement will allow the narrowest range of stormwater detention periods in the retrofitted wetland for the time series of storm inflows. Such retrofitted designs could offer enhanced water quality benefits for the more frequent low flow events as well as increased habitat protection and potential public amenity benefits.

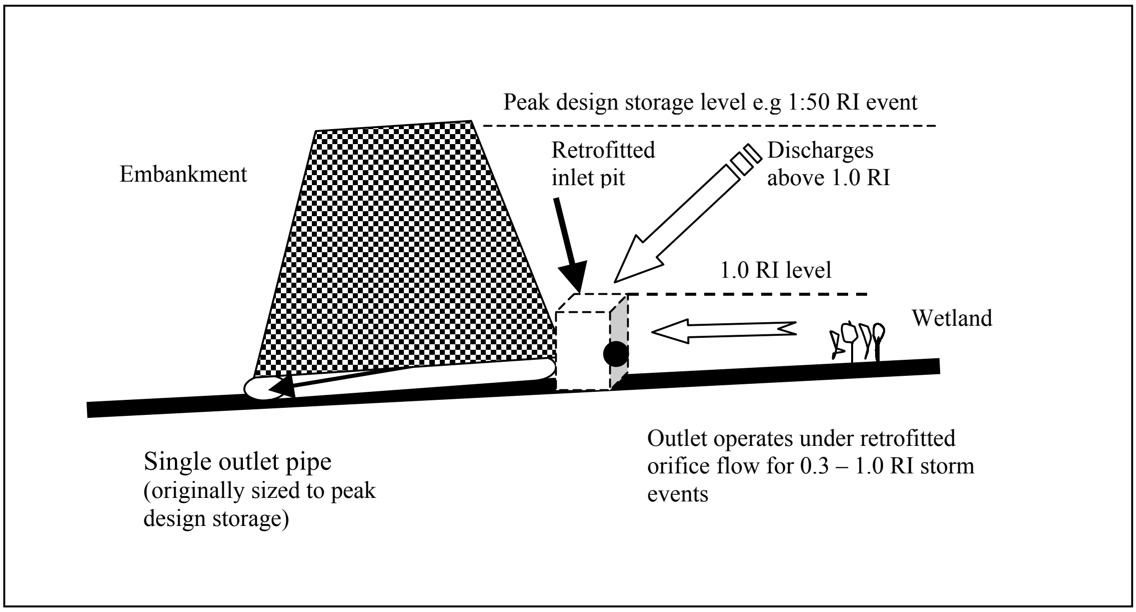


Figure 2.8. Retrofitting a Dual Outlet to Flood Storage Pond

3. PERFORMANCE AND COSTS

3.1 Wetland Performance

3.1.1 Natural and semi-natural wetlands

Very few natural wetlands within the UK are used as deliberate treatment systems for contaminated discharges. A study of four natural wetlands in Wales which receive and treat metal-contaminated mine drainage waters showed that, apart from one notable exception, removal efficiencies for most metals was generally poor and for some storm events, the wetlands themselves formed a significant source of metals to the downstream watercourse.

Semi-natural wetlands such as the Welsh Harp basin in NW London (see second box in Section 1.3.2 provide a rather better performance efficiency especially if they are actively managed to improve the wetland productivity and pollution control efficiency. As much as 54% - 61% of the total metal load in *Typha* can be stored and locked in the macrophyte rhizomes (subsurface stems) of such semi-natural wetlands.

3.1.2 Artificially constructed wetlands

Table 3.1 summarises the averages and ranges of removal percentages for various pollutants calculated from the data presented in the 1997 CIRIA report (Nuttall *et al*.,

Table 3.1. Percentage Pollutant Removals for Domestic Wastewater and Artificial Stormwater Wetland Systems in the UK

	SS	BOD	NH_4-N	NO_3-N	E.Coli
Domestic Wastewater					
Secondary treatment	83	82	18	45	68
	(69 - 94)	(70 -92)	(5 - 29)	(7 - 68)	(60 - 75)
Tertiary treatment	68	71	33	55	84
	(25 - 92)	(50 - 95)	(0 - 77)	(40 - 76)	(46 - 99)
Urban Runoff					
Wetlands	76	24	31	33	-
	(36 -95)	(-57 - 81)	(0 - 62)	(-17 - 68)	(52 - 88)
Combined Retention/Detention Basins	73			53	92
	(13 - 99)			(10 -99)	(86 - 99)
Wet (Retention) Ponds (with marginal vegetation)	55	40		29	
	(46 - 91)	(0 - 69)		(0 - 80)	
Extended Detention Basins*					
Highway Runoff	-	18		-	-
Wetlands (combined Retention/Detention)	(50 - 70)	-		(10 - 20)$^{\#}$	(50 - 90)
SF Wetlands	-	15		45$^{\#}$	82
SSF Wetlands	(13 - 75)	(5 - 32)		(10 - 60)$^{\#}$	(75 - 99)
	73			53$^{\#}$	92
	(13 - 99)			(10 - 96)$^{\#}$	(86 - 99)
	85			44$^{\#}$	88
	(62 - 97)			(25 - 98)$^{\#}$	(80 - 97)

*From US data (Urban Drainage & Flood Control District, 1992); $^{\#}$Data for Total Nitrogen

1997) for those constructed wetlands treating domestic wastewater (negative values denote negative efficiencies). The percentage removal efficiency is in most cases simply defined as: $(C_{in} - C_{out}) / C_{in} \times 100$, where C_{in} and C_{out} are the inflow and outflow pollutant concentrations respectively. The table also shows summary data that have been recorded in the UK for wetland systems receiving urban and highway runoff. The data for extended detention basins is taken from US data (Urban Drainage & Flood Control District, 1992) as there are no comparable data recorded for UK sites.

3.1.3 Metal removal efficiencies

The equivalent data for metal removal efficiencies (with ranges shown in brackets and negative values denoting negative efficiencies) that have been noted for the various types of surface water wetland systems are presented in Table 3.2. Although the data exhibit very large ranges, it is clear that artificially constructed wetlands perform better than natural systems and there is substantial evidence that water and suspended sediment metal concentrations are reduced in urban stormwater wetlands.Some possible concern has been expressed over the ability of urban wetlands to sufficiently remove cadmium, with recorded storm outflow rates frequently exceeding the EU/Environment Agency water quality standard of 5µg/l. This concern is reinforced by the evidence of wetland flushing observed in the two highway studies noted in the above box.

Metal Removal from Motorway Runoff

A study of the performance of a 3900m^2 *Typha* wetland receiving runoff from a heavily-trafficked section (140,000 AADT) of the M25 near Junction 9 at Leatherhead, showed metal removal efficiencies varying between 88% - 94%.. The final 1000m^2 settlement pond was estimated to be responsible for about 35% of this total removal rate. Zn removal efficiencies were reduced as a result of solubilisation from anoxic wetland sediments .

A study on the A34 Newbury-Bypass yielded similar evidence of soluble Zn (and Cu) being remobilised across a stormwater wetland receiving runoff from 3.1ha of the highway carriageway. The 6995m^2 SF constructed wetland (*Phragmites*) is nested within a 11,189m^2 storage basin; some 25% of the basin area is occupied by permanent standing water. The study showed an effective settling of contaminated sediment in the front-end sedimentation trap which recorded metal sediment levels generally twice as high as that within the wetland sediment. However, the range of metals contained in association with the fine (<63µm) solids fraction, was frequently greater leaving the wetland than coming in .

3.1.4 Efficiency comparison

Tables 3.1 and 3.2 show that removal efficiencies for solids range between 70 to 90% for constructed systems with comparable, but more variable removal efficiencies for metals. The performances of natural wetland systems by contrast are extremely variable and quite poor in many cases. The information available from the domestic wastewater treatment field regarding the effectiveness of constructed wetlands in pollutant removal may not be directly applicable to the use of wetland systems for non-point, stormwater runoff because of their fundamental differences. Wastewater treatment wetlands for example, are subject to constant (and fairly uniform) inflows whereas surface runoff generates pulsed stormwater loadings of varying physical and chemical composition.

Table 3.2 Wetland Metal Removal Efficiencies for Natural and Artificial Wetlands in the UK

	Metals		Cadmium	Lead	Zinc	Copper
	Total	Dissolved				
Natural Wetlands			(-38 - 50)	(-50 - 82)	(-60 - 30)	(10 - 78)
Artificial Wetlands ***1. Urban Runoff***						
Wetlands			- (5 - 73)	62 (6 - 70)	57 (-36 - 70)	51 (10 - 71)
Combined Retention/Detention Basins			- (10 - 30)	- (0 - 28)	- (3 - 22)	- (0 - 10)
2. Highway Runoff						
Wetlands	- (40 - 90)	- (-15 - 40)	- (20 - 72)	69 (-41 - 89)	42 (-36 - 71)	- (36 - 66)
Wet Retention Basins	- (45 - 85)	- (10 - 25)		52 (40 - 56)	38 (8 - 56)	
ED Basins	- (20 - 50)	- (0 - 5)				
Dry Detention Basins (with infiltration)	- (70 - 90)	- (10 - 20)				

Despite the variability recorded in pollutant removal efficiencies, some general observations can be made from the data.

- Table 3.1 reveals a broad range of pollutant removal efficiencies although the median values are fairly consistent especially for suspended solids (SS), bacteria and nutrients. The variation is not unexpected given the range of hydraulic conditions, vegetation types and coverage as well as monitoring procedures.
- suspended solids and BOD removal efficiencies tend to be more consistent in constructed wetlands intended for domestic wastewater treatment than in stormwater systems. This is most likely due to the design and management of the constructed systems as well as to the more uniform composition of inflow pollutant concentrations.
- nutrient removal efficiencies vary quite widely among all wetland types. The variations may be a function of the season, vegetation type and management of the wetland systems.
- metal removal efficiencies (Table 3.2) whilst generally variable, are better for artificially constructed systems than for natural wetlands. Under the right conditions, outflow loadings of dissolved zinc and copper can also be reduced, in comparison to inflow loadings.
- hydrocarbon removals in both semi-natural and artificial constructed wetlands is generally good.
- negative efficiencies especially for organic and metal determinands denote that wetlands can act as pollution sources. Excessive outflow loadings are normally associated with (re-)mobilisation of sediment-associated contaminants which are flushed out of the system during periods of intense stormflow activity or after prolonged dry periods. Hence, there is a need for a bypass to divert the higher

stormflow volumes away from the wetland and/or for a pre-treatment settlement basin or trench.

The efficiency ratio approach and efficiency performance data reported above are based on the average difference between inflow and outflow storm event concentrations, but a number of workers have shown that there are defects in this methodology especially when inflow concentrations are low. For example, a wet retention basin experiencing 500 mg/l TSS in the inflow and 100mg/l in the outflow would yield a higher pollutant removal efficiency than a wetland having 100 mg/l and 20 mg/l in the influent and effluent respectively. Yet the final water quality for the latter device is clearly superior and would provide more effective and efficient protection of the receiving water. This example points out the need to think carefully about whether pollutant removal efficiency, particularly when expressed only as percentage removal, is providing an accurate representation of how effective a performance is being provided by a SuDS facility. The percentage removal term is probably only really appropriate for sites and SuDS facilities subject to high pollutant input concentrations. In addition, given the dynamic nature of flow into and out of a wetland basin having a permanent mixing pool, the recorded inflow and outflow concentrations are not normally contemporaneous i.e not generated by the same storm event.

The type of inlet structure and the flow patterns through the wetland will also significantly affect pollutant removal. This will be additionally influenced by seasonal changes which occur in vegetational productivity, hydraulic retention time and microbial activity. It is not yet feasible to provide definitive designs to meet specified and consistent performance requirements for given storm and catchment characteristics or to meet specific receiving water standards and storm return periods. In view of the diverse range of pollutant and stormflow loads and reduction requirements, as well as the local physical, social and economic constraints, the design, operation and maintenance requirements will also tend to be site specific.

Nevertheless, whilst accepting this qualification, it is still possible from the data and information currently available to broadly identify representative pollutant removal and flow attenuation capacities for various sustainable urban drainage options including wetland systems. Table 3.3 attempts to summarise these capabilities and provide an overview of the potential performances that each wetland option might be reasonably expected to achieve. The various SuDS designs undoubtedly vary in their ability to reduce the different types of pollution arising from urban development although each can also offer additional environmental benefits. It is therefore important that the designer, developer and regulator establish what the general and/or specific objectives are before selecting a particular SuDS type. After establishing what the flood control, water quality and amenity objectives are, an analysis is then required of what is feasible on a particular site given the characteristic physical, meteorological, economic and institutional constraints.

3.1.5 Defining wetland pollutant removal rates

The treatment performance of wetland systems has been described by various mathematical models but given the reasonable assumption that constructed wetland systems operate as attached-growth biological reactors, their performance can be estimated from plug flow kinetics based on first-order decay (or assimilative) "k" rates for specific pollutants. First-order kinetics implies that the rate of change of pollutant concentration with time is proportional to the concentration and plug flow implies that stormwater entering the reactor flows as a coherent body along the length of the reactor. The change in concentration during the retention time in the reactor is therefore dependent solely on processes occurring within the plug flow. The basic equation under these conditions describing the first-order area-based wetland pollutant removal rate (J; $g/m^2/yr$) is of the form:

> **Plug Flow Reactor Model**
> Given plug flow conditions and with constant water volume, exponential pollutant profiles can be predicted as:
> $$\ln [(C_{out} - C^*) / (C_{in} - C^*)] = -k_T y / HLR$$
> [or as: $(C_{out} / C_{in} = \exp(-k_T HLR)$ and $k = HLR(\ln C_{in} - \ln C_{out})$]
> and $C_{out} = C^* + (C_{in} - C^*)\, e^{-kA/HLR}$
> where C_{in} and C_{out} are pollutant inflow and outflow concentrations (mg/l) respectively, C^* is the wetland pollutant background concentration (mg/l), y is the fractional distance (x) through the wetland length (L,m) i.e = x/L, k_T is the temperature dependent (area-based) first-order rate constant (m/yr), A is the wetland surface area (m^2) and HLR the Hydraulic Loading Rate (m/yr).
> Rate constants can be corrected for temperature effects by:
> $$k_T = k_{20}\, \theta^{(T-20)}$$
> where k_T and k_{20} are the reaction rate constants at T^O C and 20^O C respectively (m/yr) and θ is an empirically derived temperature correction factor (normally 1.09).

$$J = -k\,(C - C^*)$$

where k is the pollutant decay rate constant (m/yr) with C and C^* being the wetland and background pollutant concentrations (g/m^3) respectively. However, k is a lumped parameter representing a deposition rate in the case of solids and bacteria, a biodegradation rate for organics (BOD) and a reaction rate in the case of nutrients, metals and hydrocarbons. Thus the value of k really depends on the relevant operating "treatment" process and is normally expressed as a synthesised index value combining the differing removal processes. Any factor such as hydraulic retention time (HRT) which influences these processes can indirectly affect the final k value.

Although simple, this k - C^* area-based reduction model, adapted for treatment wetlands by Kadlec and Knight (1996), represents the highest level of complexity that can generally be calibrated with wetland data and provides a reasonable approximation of performance for a wide range of stormwater pollutants. Appendix B provides detail of the working method and illustrates how plug flow kinetic modelling approaches based on the first-order reaction rates can be applied to determine the size and residence time required to achieve target pollutant reduction in wetland systems.

However, despite the general utility of the k - C^* model it has not been universally accepted as it assumes spatially invariant time-averaged flow which is difficult to apply to urban wetlands under stormflow conditions. Rainfall will cause dilution and shorten retention times and such "augmentation" can lead to errors by as much as a factor of four in the determination of rate constants for a first-order reaction. Some guidance on deviation from the simple scheme can be obtained from Kadlec and Knight (1996) who argue that SF constructed wetlands have characteristics intermediate between plug flow and well mixed. The k - C^* two-parameter model also does not account for adaptation trends in the wetland ecosystem as it matures or the effects of pH and dissolved oxygen as well as other factors which are known to affect the fate of pollutants in treatment systems. More complex models incorporating the effects of plant biomass, pulsed flows and varying residence times are available but these require substantial calibration data and further field testing before they can be universally and simply applied to constructed urban stormwater wetlands.

3.2 Performance Indicators

Table 3.4 provides a qualitative summary of best practice guidance indicators in respect of wetland and dry/wet storage basin facilities. The table is intended to give first-screening evaluation of the robustness of the various wetland systems to achieve the stated functional objective. High design robustness gives a significant impact and probability of performing as intended. Low robustness and impact implies that there are many uncertainties with regard to how the design will perform for that function. The evaluation is both subjective and tentative being based on a review of the literature and by the working experience of the authors. Nevertheless it does indicate that wetland systems have a considerable potential to address all three elements of the SuDS triangle i.e water quantity, water quality and amenity/habitat

Table 3.4 Wetland and Dry/Wet Storage Basin Indicators

	Pollutant Category				**Flood Abatement**		**Amenity**	
	Floating Debris	Sediment And Litter		Dissolved	Runoff Reduction	Peak Flow Reduction (with appropriate overflow control)	Open Space & Recreation	Landscape Quality, Habitat & Biodiversity
		Coarse	Fine					
Natural Wetlands	+	+ +	+ +	+	+	+ +		+ + +
Constructed Wetlands	+	+ + +	+ +	+		+ +	+	+ +
ED Basins	+	+ +	+			+ +	+ +	+
Dry Detention Basins	+	+ + +	+		+ + (Infiltration Basin)	+ + +	+ +	
Wet Retention Basins	+	+ +	+ +	+		+ +	++	+ +

Key: + minor impact; + + medium impact; + + + major impact.

Table 3.3 SuDS Pollutant Removal and Flow Attenuation Capacities

	Percentage Pollutant Removal Efficiency							Flow Attenuation Efficiency	
	Litter and Debris	Solids	BOD	P	N	Metals	Bacteria	Peak (allowable discharges)	Volume
Wetlands (Combined Ret/Det Basins)	NA	▒	⁙—⊞	⊞—▒	⁙—⊞	▒	⊞—■	⁙—⊞	□
Wet Retention Basins (With marginal vegetation)	NA	▒—■	⊞	⊞—▒	⁙	⊞—▒	⁙—⊞	⊞—▒	⁙
ED Basins (<10 hour detention; with marsh)	■	▒	⁙	⁙	⁙	⊞	?	▒	□
ED Basins (10-24 hour detention; with marsh)	■	■	⊞	⁙—▒	⁙	▒	? --- □	▒	⁙
Dry Detention Basin (First flush infiltration)	■	▒	▒	⊞	⁙—⊞	⊞	⁙	▒	⁙—⊞
Dry Detention Basin (Total infiltration)	■	■	▒	▒	⊞—▒	■	■	▒	▒—■

KEY: ■ 80-100%; ▒ 60-80%; ⊞0-60%; ⁙-40%; □0%

? Insufficient knowledge NA; Not applicable

- Level of pollutant removal will be subject to basin volume or surface areas relative to catchment runoff
- In silty clay/clay soils, high basin volumes or surface areas relative to catchment runoff will be required
- Flow attenuation in Retention and Detention Basins is a function of storm frequency, storage provision and outlet control

3.3 Treatment, Performance and Maintenance Costs

A variety of factors will affect the operational costs of treatment wetlands of which perhaps hydraulic retention time (HRT) is one of the most significant. Figure 3.1 is based on data for SSF wetland systems derived from the 1999 US EPA National Stormwater BMP Database which illustrates the cost of building such wetlands as a function of flow rate multiplied by retention time. Costs are presented in this way

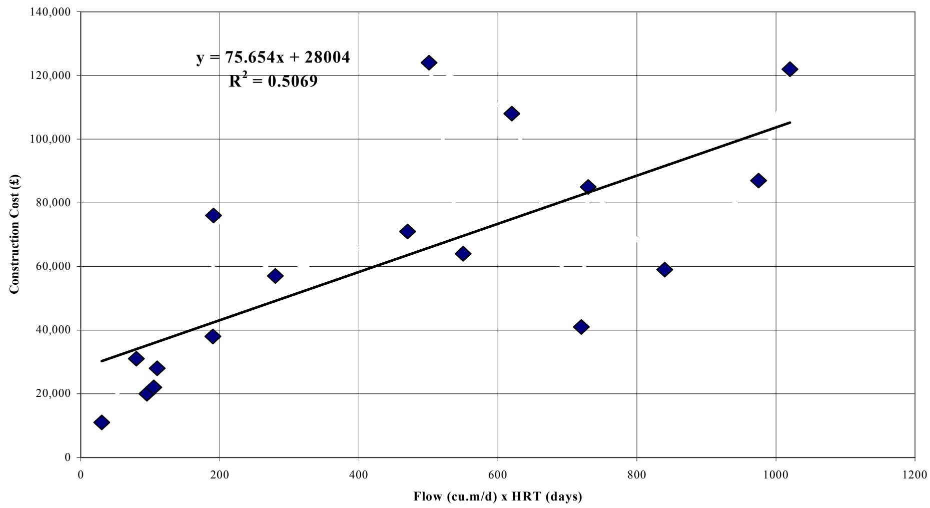


Figure 3.1 SSF Wetland Performance Costs

because wetland designs can have different treatment objectives e.g targeted suspended solids removals will require very different retention times than for nitrogen. Two similar flow rates having different treatment design objectives will therefore have very different costs. The figure is based on the assumption that longer retention times lead to improved water quality and although the linear fit has a relatively poor correlation, it does give a rough estimate of costs. Thus based on the "best-fit" equation, a $50m^3$/day SSF wetland system with 24 hours of treatment would cost £31,786. Otimisation techniques used in Sydney yield costings of £20-22/m^2 for urban stormwater constructed wetlands but note that there are steep increases in costs if more than 80 - 85% pollutant removal rates are required.

Very little data are available on cost criteria for UK wetland systems and what cost guidance is available is generally restricted to constructed wetlands intended for domestic or industrial wastewater .The general distribution of capital costs between typical design, engineering and development elements for stormwater wetland systems can be estimated as shown in Table 3.5. This table clearly shows the additional costs over and above a conventional flood detention basin required for lining, providing a suitable substrate and planting in a wetland system. Suitable nursery stock of plants including planting for example, can cost around £3 - 5/m^2. For a typical stormwater flood detention basin, the sum of all costs related to

Table 3.5 Distribution of Wetland Capital Costs

Item	SF Wetland	SSF Wetland
Geotechnical testing, excavation, compaction etc	16% - 20%	10% - 17%
Substrates (SF); Gravel (SSF)	3% - 5%	30% - 40%
Geotextile liner	20% - 25%	15%
Plants	10% - 12%	10% - 12%
Control structures	10% - 15%	5% - 10%
Formwork, pipework etc	10% - 12%	5% - 8%
Design and Landscaping	8% - 12%	6% - 13%
Others (incl. contingencies)	6% - 10%	6% - 10%

design, consenting and legal fees, geotechnical testing and landscaping is equivalent to about 30% of the base construction cost (excavation, control structures and appurtenances e.g litter racks, rip-rap etc). If wetlands are incorporated (or retrofitted) into the detention basin, these costs increase by anything between 15 - 37% of the base construction cost. The IWA (2000) report suggests that the capital cost of a SSF wetland is 3 to 5 times that of a SF wetland to do the same job. Thus on the basis of performance to cost, it would seem difficult to justify SSF systems for stormwater treatment apart from any wish to keep the polluted water below the surface of the ground or media. Halcrow & Middlesex University (2000) have estimated the total cost of a 1750m^3 cellular highway wetland (with front-end 500m^3 sedimentation trench, 2000m^2 constructed wetland and 50m^3 final settlement pond), as being £144,500 based on the 1995 CESM3 Price Database. Some 30% of this total is taken up by the geotextile liner cost (£15-20/m^2). The inclusion of a Class I bypass oil interceptor would increase the cost by an additional £5000 for a 200 - 1300 l/s peak flow unit. However, given that few stormwater wetlands are likely to be much larger than 0.5 - 0.75ha, land costs (especially on greenfield sites) represent only a minor proportion of total costs. It must also be borne in mind that the final "reclaim" value of the wetland site is unlikely to depreciate and thus the net present worth of the land following the nominal operational lifetime (say 20 - 25 years) should be considered as a credit in any economic evaluation.

Table 3.6 gives an indication of both capital and maintenance costs for a variety of source control systems. Wetland systems have low intrinsic Operational & Maintenance (O & M) costs which are also lower than conventional hard engineered" drainage systems by a factor of 2 to 10. The costs indicated in Table 3.6 for operational maintenance suggest that they are insignificant compared to the initial capital investment although disposal of contaminated sediment as a hazardous waste (£50-60/m^3), replanting (about £3-5/m^2) and macrophyte harvesting could be expensive and labour-intensive items.

The large range in costings shown in Table 3.6 for some treatment systems largely reflects local sizing requirements for particular devices which can especially influence for example, the final costs of retention basins and wetland systems. The 1999 US EPA National Stormwater BMP Database quotes a general average median annual O & M cost for SF constructed wetlands equivalent to £600/ha wetland surface area. Most O & M costs do not normally include monitoring costs despite the fact that for successful system control, wetlands should be regularly monitored (monthly to quarterly) for at least inflow and outflow water quality, water levels, sediment accumulation and indications of biological condition.

Table 3.6 Capital and Maintenance costs for Highway Treatment systems

Treatment Device	Capital Cost (£'000s)	Maintenance Cost (£/per yr)	Comments
Gully/Carrier Pipe system	150 - 220	1000	No fin drainage allowed for in costs
Grass swale	15 - 40	350	Requires replacement after 10-12 years
Oil interceptors (with grit chamber)	5 - 30	300 - 400	
Sedimentation tank	30 - 80	300 - 350	Without sediment disposal
Sedimentation lagoon/basin	45 - 100	500 - 2000	Without sediment disposal
Retention (balancing) basin	15 - 300	250 - 1000	With no vegetation or off-site dewatering and disposal of sludge and cuttings
Wetland basin	15 - 160	200 - 250	Annual maintenance for first 5 years (declining to £80 - £100/yr after 3 years). Sediment disposal required after about 10-15 years.
Combined treatment train system	100 - 300	2000 - 3000	Assume grass swale, oil/grit interceptor, sediment forebay and wetland cells

Institution of Highways & Transportation 2001

A comparison of the annual maintenance costs (excluding monitoring) for conventional v SuDS drainage for the M42 Hopwood Park motorway service station indicated a saving of some £1220 pa (Bray, 2001b). A 6 month cleaning routine for a conventional gully chamber and oil interceptor is estimated at £1204 pa against an estimated cost for maintenance of an individual wetland component within the SuDS design of about £250 pa. The costings for annual maintenance of the SuDS scheme at the M40 Oxford motorway service station (see Section 4.1.1), was estimated at being £917 more than for an equivalent conventional drainage scheme (which would total £2800 pa) but with an annual maintenance saving of £7500 (CIRIA, 2001). The retrofitting of permeable paving and wetland drainage to the Lutra House, Preston site of the Environment Agency has proved to be no more expensive than using a conventional piped system. The limited cost comparisons available for operation and maintenance of wetland SuDS suggest that they may lie within ±10 - 20% of conventional drainage systems. Cost-performance analysis using HydroWorks modelling for conventional drainage and the CIRIA (2000b) SuDS methodology, has suggested that SuDS are generally economically viable within those urban catchments (and especially greenfield sites) having large areas or numbers of opportunities for their implementation such as permeable soils and large open spaces.

There is undoubtedly a lack of general awareness of the need for and magnitude of maintenance associated with all SuDS devices including urban stormwater wetland and a general failure to regularly perform both routine and non-routine maintenance tasks. It is quite likely that both the performance and longevity of all SuDS urban wetlands will decline without adequate maintenance. In general terms, over an expected 25 - 30 years lifetime, the full maintenance cost of such SuDS facilities could well be equivalent to the initial construction costs. Given this, the adopting and managing authorities need to carefully and fully evaluate how such long-term, future maintenance costs are to be covered.

The provision of attractive landscaping features which enhance the views from vantage points around a stormwater wetland facility can offer tangible landscape value and amenity benefits which can offset total costs. Some evidence for this value can be seen from increases in land values and house prices located adjacent to water features. Some estimates suggest that a stormwater wetland "waterfront" location on a business park/commercial estate can increase rentals by up to one-third and individual residential property prices by 3% to 13%. It is clear that landscaping and amenity upgrading of wetlands and urban lakes will stimulate the perceived attractiveness of the wider surrounding corridor and adjacent areas. Additionally, the more positive the local public attitude towards increases of development (or public) investments, the larger the sum they are willing to pay to use any amenity and recreational facilities provided on the site. The surface drainage "water gardens" and surrounding grass "buffer" zones on the Aztec West Business Park close to the M4/M5 junction north of Bristol, were designed to integrate habitat and nature conservation with everyday working life. It has been suggested that this landscaping provision increased the ground rents on the business park by as much as two to three times.

4. OPERATION AND MAINTENANCE

4.1 Wetland Operation and Maintenance Requirements

4.1.1 Introduction

Regular inspections of constructed wetlands must be undertaken to ensure their proper and continued function. If no maintenance regime is adopted, then experience has shown that early failure is likely to occur on many sites. The problems that most frequently occur are blockages of inlets/outlets, flow regulating devices, siltation of storage areas, algal growth and plant dieback. This means that responsibilities and maintenance routines for maintenance and servicing schedules need to be clearly identified at an early stage and a distinction made between crisis (remedial) maintenance and regular "good practice" maintenance . Bray (2001) has developed a full maintenance inspection check list intended for the M42 Hopwood Park motorway service station area which for the wetland components in the SuDS design suggest maintenance intervals which vary between monthly (inlet, outlet, drop structures), annually (grass cutting) and bi-annually (valve checks, wetland sediment/plants etc). In practice, the maintenance frequency will be determined normally by site-specific needs. but maintenance operations should include:

- checking inlet and outlet structures
- checking weir settings
- cleaning-off surfaces where solids and floatable substances have accumulated to an extent that they may block flows
- removal of gross litter/solids
- checking sediment accumulation levels (wetlands, sediment traps, infiltration trenches etc..)
- bank erosion
- general maintenance of the appearance and status of the vegetation and any surrounding landscaped zones.

The operation and maintenance procedures connected with a constructed wetland are anticipated to include:

- jetting/cleaning sediment traps, removal of sediment;
- maintenance of the substrate and plants;
- harvesting;
- maintenance of water levels;
- maintenance of nutrient levels;
- general structure maintenance; and
- control of weed growth.

These are described in more detail below and an outline O & M schedule is given in Appendix E. To carry out the operation and maintenance requirements, "all-weather" vehicular access is required to all constructed wetlands.

4.1.2 Removal of sediment

During the construction phase it is important that steps are taken to ensure that minimal amounts of sediment are allowed to enter a constructed wetland system. Therefore, ideally the constructed wetland should be built as late as possible in a highway construction programme and the surrounding banks should be vegetated as early as possible to prevent the in-wash of both sediments and nutrients

In the post-construction phase, sediments will require removal from settlement trenches, ponds and final settlement tank, if present. The purpose of the constructed wetland is to isolate and contain the pollutants originating from urban and highway runoff, either as settled solids or within organic tissue, and prevent them from entering the water body. Some of the polluting agents will be degraded through biological processes, but many will persist in the settled sediment and will ultimately need to be removed and disposed off-site. An effective maintenance programme will need to be designed. Sediment is likely to be classified as hazardous waste and may require de-watering on site prior to disposal at a licensed waste facility. It is suggested that the routine maintenance programme includes a minimum frequency of annual inspections to assess whether sediment removal is necessary and inspection following major storm events to assess whether litter and gross solids have been introduced and need removing. This periodicity can be subsequently reviewed based on experience.

It has been suggested that sediment removal will not be required before 10 - 15 years although this operational lifespan will depend on local sedimentation rates and on whether the wetland basin was subject to solids accumulation during the constructional phases. The relationship between available storage volume and solids removal efficiency provides one basis for determining when sediment removal may be required. Field determination of accumulated sediment during regular inspection periods (Figure 4.1) can provide a useful diagnostic method for predicting when such sediment removal is likely to be necessary.

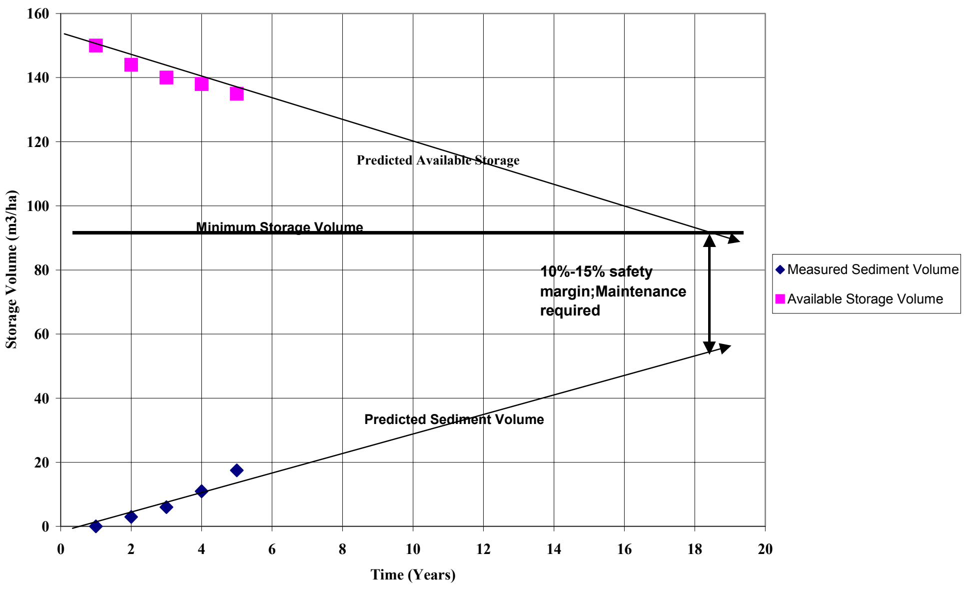


Figure 4.1 Predicting Sediment Removal Maintenance Requirement Time

4.1.3 Maintenance of the substrate and plants

Maintenance requirements of constructed wetlands typically involve ensuring continued hydraulic conductivity of the substrate (by washing or replacement), removal of accumulated sludges in the settlement pond and inlet area of the wetland; removal of decaying algae and macrophytes in the settlement trenches, pre-treatment ponds and final settlement ponds and replacement of moribund areas of vegetation.

It is likely that constructed wetlands intended for urban and highway runoff treatment will only require significant maintenance between 15 and 25 years following commissioning. However, as more information is collected on systems for treating highly loaded sites such as those serving heavily-trafficked catchments, the figure for this maintenance period may change. Depending on the pollutant loadings it is expected that the maintenance will involve cleaning or removal of sections of contaminated substrate and the associated vegetation. To enable treatment to continue, only sections of the bed should be removed at any one time, or beds should be partitioned to allow one component to be restored. Plant replacement may be required if the vegetation has been devastated by pests such as blackfly or greenfly. If the problem is noticed in time it may be possible to spray the plants. Biological control by ladybird beetles may prevent these infestations as the wetland matures. However, the occurrence is difficult to predict as the infestation will depend on factors such as location, alternative food sources in the area and winter severity.

It should be noted that any use of herbicide or pesticide in or near water courses (and this would include reedbeds) will require the prior approval of the Environment Agency.

4.1.4 Harvesting

The majority of constructed wetlands are not subjected to harvesting by removal of plant material as it is considered that the plant litter layer has a role to play in the treatment process by providing thermal insulation for the substrate and a large surface area of particles from decomposed leaves for the adsorption of metals. However, the harvesting of leaf material from constructed wetlands installed to treat road runoff, will remove metals that have bio-accumulated , and thus help to prolong the wetland life span. However, there is not enough information available at present to decide whether or not harvesting is preferable.

4.1.5 Maintenance of water levels

A suitable outlet control should be installed to regulate the water level; a flexible plastic pipe linked to a chain is an appropriate low cost option (Cooper *et* al., 1996). Adjustment of water levels may be required during planting or periods of drought. The most expensive maintenance cost would be incurred for replanting if for example, during a prolonged dry period the wetland was allowed to dry out sufficiently to severely wilt or kill the plants. Again, there is little information available on the hardiness of plants to dry conditions and the critical length of such dry periods. It is known that *Typha latifolia* requires a water level to be maintained at or above the surface of the substrate (see Sections 2.3 and 2.4). Possible prevention measures include:

- tankering in water from a nearby water source when necessary;
- diverting water into the wetland from adjacent water courses by gravity, if the topography and water levels allow; or
- active pumping of water from a nearby water source such as a river or ground water aquifer via a borehole. If no electricity supply is available in the area solar powered pumps could be considered.

The problem of plants dying from lack of water is unlikely to occur every year in the UK (ie only during summer droughts). Therefore the cost of preventing the problem should be a key factor in deciding on the appropriate solution. Until more information is available on the frequency and severity of the problem, it is suggested that if water cannot be conveniently diverted from a nearby water source by gravity, then the maintenance programme should include tankering in water if necessary. At this stage, it does not appear to be economical to install a permanent pumping arrangement.

4.1.6 Maintaining nutrient levels

Constructed wetlands treating road runoff will receive few nutrients. However, nutrient concentrations in urban runoff will vary with the density of gardens and parks within the catchment . Therefore, it may be necessary to spread slow release fertiliser pellets periodically. There is not enough information available at present to determine the necessity or frequency of such fertiliser application.

4.1.7 Control of weed growth and algae

Periodic flooding of the constructed wetland may be necessary to control weed growth when the reeds and aquatic plants are initially growing to maturity. However, the density of reeds at maturity would considerably reduce or eliminate the possibility of weed growth. A flooding depth of 0.05m is sufficient, which is at the lower end of the recommended maximum range of water depths for *Phragmites australis* (IWA, 2000).

Filamentous algae and blooms of unicellular algae may develop in settlement trenches and ponds. Cylindrical bales of barley straw wrapped in hessian are being used successfully on selected treatment wetlands on the A34 Newbury Bypass to eliminate algal infestations.

4.1.8 Monitoring

Monitoring is extremely important to ensure a successful operational performance and early detection of changes in wetland performance requires adequate data collection and analysis. All urban stormwater wetlands should be systematically monitored for at least inflow and outflow water quality (concentrations and loadings), flow characteristics and evidence of short circuiting, water levels and indicators of biological condition, preferably monthly and minimally on a quarterly seasonal basis. Nuisance species, weed growth and biological condition of the plants should also be noted such as reduced lengths of longest leaves, chlorosis or loss of green leaf coloration and curling of the plant leaf tips etc. Water quality parameters should include temperature, pH, conductivity, DO, BOD, TSS with metals, hydrocarbons and nutrients as required, together with information on sediment depth. One storm event during each season should also be sampled to provide information on short-term storm event performance.

5. WILDLIFE AND LANDSCAPE ENHANCEMENT

5.1 Introduction

The provision of attractive landscape features which enhance the views from vantage points around a wetland and from surrounding areas can offer tangible landscape value and amenity benefits. There should be a clear human involvement in the wetland ecosystem. This can be engendered by paths/walkways, boardwalks, seats, jetties, attractive views, educational material (brochures, trail guides etc.) and display (including electronic) interpretation boards. A sense of ownership can be increased through involvement of the surrounding community in the design process, planting days, educational trails and so on. However, proper and continued development of the amenity and wildlife functions requires ongoing and active management.

> **Wetland Amenity Benefits**
>
> People find water intrinsically attractive and wetlands create a natural focal point in any landscape. Opportunities that add to a wetland amenity include:
> - creation of views over water
> - designing in "reflection" pools
> - creation of "visual surprises" through strategic siting of marginal/surrounding vegetation and gaps through marginal spoil mounds
> - provision of wetland access, public open space, walks, jetties and boardwalks, picnic facilities etc
> - use of soft engineering techniques e.g. wood, vegetation palettes, anchored willow branches etc

5.2 Landscape and Visual Issues

The use of vegetation is often considered to be a more attractive feature within the landscape than a concrete/brick treatment system with no vegetation. However, constructed wetlands for the treatment of urban and road runoff may well be located in places that are not their natural habitat. Their alien appearance may be accentuated by the design of regular shaped beds. Constructed wetlands can be designed to fit in with the natural environment and the following is a list of basic principles that should ideally be used at the design stage:

- the adoption of a straight-sided, square or rectangular-shaped constructed wetlands should be avoided. Curved-sides will assist in giving the constructed wetland a natural appearance and creation of bays will provide varying territories for aquatic birds.
- the lie of the land should be used to determine the appropriate site for the constructed wetland. Use should be made of natural dips and hollows, which will reflect the likely position for a reedbed.
- the use of additional plant species especially in the margins of a wetland would provide more visual appeal than a monoculture. It would also enhance the wildlife interest of the wetland.
- planting of appropriate herb and shrub species around the constructed wetland may visually enhance the area and provide an opportunity for screening and restricting public access. The planting of trees near the wetland should be avoided to prevent shading, invasion of roots and damage to any wetland liner.

Visual impacts that should be considered include those from the road and surrounding areas, particularly for local residents and from adjacent viewpoints. Visual impacts will occur, and will be different, both during construction and during operation of the constructed wetland and both will require consideration. Although the vegetated area can be made to appear "natural", associated infrastructure may introduce unnatural, man-made development. This may include access routes, parking areas, inlet and outlet structures and settlement ponds.

The significance of the visual impacts will depend upon the sensitivity of the landscape. For example, if it is in a designated area, such as an Area of Outstanding Natural Beauty (AONB), then the significance of any detrimental impacts may be high. Another consideration is the visibility of the site, including whether it is likely to be seen from a residential or other well-used area. A constructed stormwater wetland can enhance the visual appearance of the site, but this may not always be the case. In particular the removal of features of landscape importance to create constructed urban wetlands may be damaging to the local environment.

5.3 Landscape Development

Multifunctional development may also require the provision of special facilities which need to be landscaped into the overall wetland basin design (Ellis *et al.*, 1990). For example, edge form may include the use of structures such as jetties, boardwalks, viewing platforms and the judicious but limited use of engineering materials such as stone or rip-rap. If cement or mortar is not used to lay the flags/stones, the intervening spaces can provide space for the colonisation of vegetation including wild flower species. The design should ensure that the wetland basin fits in with the surrounding landscape and that grassed areas with seating and viewing positions are provided. An example of a schematic landscaping design for a wetland retention basin is given in Figure 5.1 and which is based on a synthesis of landscaping features incorporated into the surface water balancing basins located within the Ouzel Valley around Milton Keynes. The areas should develop a strong and definite theme or character. This might be generated from particular views and topographic features around the wetland site or based on the cultural character and setting of the surrounding neighbourhood.

Many schools and particularly primary schools in urban areas, are attempting to utilise existing "natural" areas including local wetlands and flood storage basins as outdoor classrooms for environmental studies. The success of the London Kings Cross Camley Street Local Nature Reserve (LNR) wetland attests to the intrinsic value of this educational function. This central city wetland fully involves the local

Designing Safe Wetlands

- carry out a risk assessment/safety audit
- provide warning signs and safety/rescue equipment where necessary and conduct regular inspections of all equipment and signage
- design wetlands with side slopes of no more than 1 in 4; good ecological design will normally give much gentler slopes than this anyway
- establish barrier planting schemes (hawthorn, scrub etc.,) to prevent access where necessary
- consider use of low fencing if necessary to prevent access to the water by young children

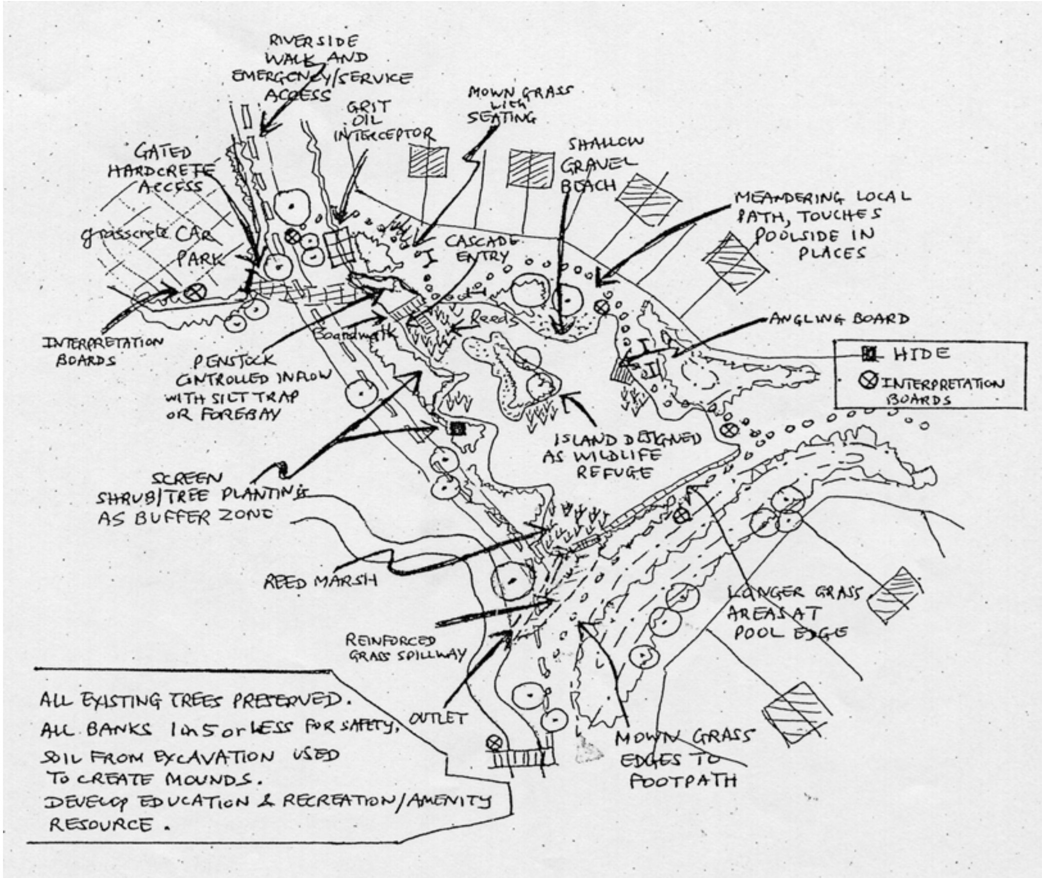


Figure 5.1 Schematic Landscaping for a Wet Retention and Wetland Basin.

community, schools and colleges as an integral element in the operation of the nature reserve thus entirely fulfilling the objectives of Local Agenda 21. The urban park reserve has made a considerable impact not only at the local level but also at the national and international level. It provides a model for further development and emphasises that the size of an urban lake park need not be a key factor in determining its role in conservation, recreation, education and landscape enhancement.

The Great Notley Garden Village development near Braintree, Essex also illustrates an imaginative landscaping approach to new greenfield housing sites. The 188 ha housing development includes a country park with an ornamental pond together with wetland and surrounding landscaped pasture and woodland providing wildlife habitats and a central focus for community relaxation and recreation. The 7900m^2 constructed wetland (Figure 5.2 and adjacent 16,000m^2 recreational pond at the site have been designed not only to provide flood storage and stormwater treatment but also an integrated community facility. The wetland structures have been adopted by Anglian and Thames Water with the wetland itself and surrounding landscaping and park areas adopted by the local authority. In this respect, the site fulfils the objectives of Environment Agency environmental policy for new urban developments which give sustainable added-value in terms of enhanced community landscape which is at the same time consonant with wildlife and conservation requirements as well as with flood storage and water quality needs. The country park style development with an ornamental pond and wetland setting within surrounding woodland and grassland, provides a naturalistic wildlife habitat and a central focus for community relaxation and amenity providing both flood water storage and aesthetic appeal . Figure 5.2 illustrates the range of landscaping features that have been incorporated into the design of the stormwater constructed wetland.

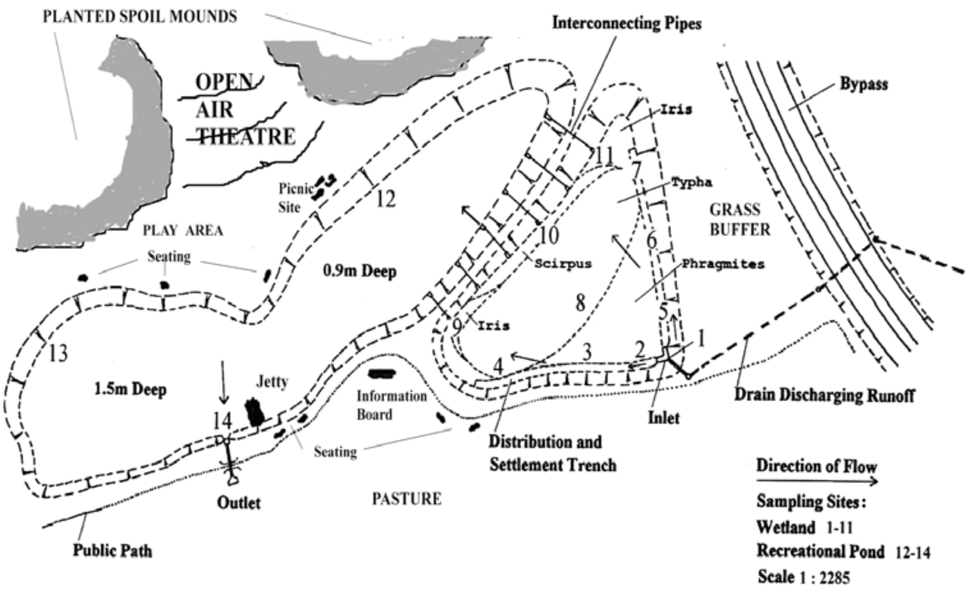


Figure 5.2 The Great Notley Garden Village Wetland

5.4 Wetland Wildlife Considerations

The use of vegetation, with the inevitable micro-organisms (whether introduced or naturally colonised), in effect constitutes a wetland habitat which is likely to prove attractive to a range of other wildlife species. A range of common plants and animals which are quite tolerant of pollutants, particularly air breathing invertebrates such as water beetles, bugs and water snails, will quickly colonise ponds located in close proximity (within 1 km) of existing watercourses and wetlands.

In designing a favourable system, various wetland ecological considerations need to be made to ensure the success of the scheme including:

- a small constructed wetland system based on a monoculture will have limited value, compared with an integrated treatment system containing a range of plant species and permanent open water.
- in order to realise the full potential of wetlands, careful consideration should be given to the incorporation of detention basins upstream and downstream of the wetland. In addition to sediment settlement provision, these water bodies can be expected to be attractive to aquatic invertebrates, amphibians and waterfowl.

Costs of Wetland Ecological Management

- creating 5 small 1 m^2 pools in the drawdown zone of a large wetland to provide additional habitat for water beetles: £1000 (or 5 person/days)
- herbicide spraying by professional contractors to control invasive alien plants: £5 per 10 m^2
- removing sediment (<20 m^3) manually to create local diversity: up to 50 volunteer personnel/days
- selective tree coppicing along 20 m of wetland margins: £500
- installation of dipping platform: £1000
- production and installation of laminated interpretation boards: £1000+
- dredging: £50 per m^3 plus £3 per m^3 for spoil taken off-site

- reedbeds should not be constructed in the shade of trees as this can lead to poor patchy growth.
- some plants will out-compete other species. Flooded conditions enable reeds to out-compete other species and this is a good method of weed control. Reeds (*Phragmites*) will displace bulrush (*Schoenoplectus*) and reedmace (*Typha*). However, reeds suffer competition from other species such as reed canary grass (*Phalaris*) and Iris in drained systems. The introduction of invasive exotic species such as *Crassula helmsii* will severely detract from the intrinsic conservation value of the wetland SuDS and their potential to contribute to local biodiversity planning. More seriously it creates a stepping stone from which invasive alien species can colonise local water bodies that support a high quality native vegetation, which may be threatened by the competitive nature of these alien species.
- reedbeds should not be planted near willow trees (*Salix*) since seeds will be deposited into the wetland bed and the resulting willow trees, with deep roots, may damage any liner that is present (Cooper *et al*., 1996).
- the creation of undulating "hummocky margins" in shallow waters of retrofitted wetland designs; these mimic the natural physical diversity of semi-natural habitats. Smooth finished surfaces provide less physical habitat diversity for animals.
- shallow water and nutrient-rich wet mud provides ideal habitat for amphibians and invertebrates. This is a key habitat for many small annual wetland plant species that is often lost in the later stages of pond succession.
- spits and islands encourage invertebrates and wildfowl; grazing and trampling by wildfowl will also often diversify marginal wetland habitats.
- the encouragement of a mosaic development of marginal plants to maximise habitat structural diversity eg *Glyceria fluitans* (floating sweet-grass) which provides good habitat for newts and other invertebrates.
- the checking of planting schemes one and two years after establishment to ensure that specifications have been carried out and undertake immediate remedial action if invasive species are found.
- the land adjacent to the SUDS wetland can provide important terrestrial (foraging and hibernation) habitat for amphibians and nesting birds where managed sensitively. The vegetation should remain largely uncut to provide cover and should be planted only with native trees and shrubs such as willow (*Salix fragilis* or *Salix caprea*), alder, ash and hawthorn.
- including wherever possible, a short after-care programme about one year after creation. Use this to (a) undertake fine-tuning of the wetland design and (b) to capitalise on new opportunities that may have arisen e.g re-profiling margins, natural seepage to create new pools etc. Fine-tuning of this sort costs very little but will often greatly increase the biodiversity value.

The management of fish in wetlands should aim to promote a community which minimises the effect on algal and submerged water plant growth. Fish may influence lake ecology by selective predation of zooplankton which in turn reduces the grazing pressure on phytoplankton and increases the tendency for algal blooms to occur. One of the principal fish species responsible for these problems is the Bream. Fish may also be involved in nutrient recycling through feeding on the sediments and through digestion of particulate organic matter. Carp has been identified as a principal agent of such pathways. Carp and bream populations should be reduced and the wetland restocked with tench and crucian carp which have a less damaging effect. Pike can also be added as a predator when water clarity has improved .

Consideration must also be given to the potential for stormwater constructed wetlands to be harmful to the wildlife they attract as a result of direct poisoning or through pollutant bio-accumulation. A number of further issues in relation to wetland ecology and wildlife (see section 8.7) may also need to be considered as wetlands are introduced for urban stormwater treatment over the next 5 to 10 years.

6. SuDS IMPLEMENTATION AND CATCHMENT PLANNING

6.1 Introduction: The Need for Integrated Approaches

SuDS do not operate as a series of isolated drainage devices but should be designed and operated holistically and they must work in conjunction with conventional drainage systems. The viability and success of such an integrated approach needs coordinated participation of all stakeholders within a catchment-wide planning framework.

Principal Stakeholders in Urban Surface Water Drainage

- The Environment Agency
- Local Councils
- Water companies
- Highway authorities
- Developers
- Non-Governmental Organisations (NGOs)
- Riparian owners

Urban wetland SuDS systems that function as flow and/or water quality control facilities for stormwater runoff normally discharge to controlled receiving waters within a defined catchment. It is therefore appropriate to review relevant catchment-based UK legislative and planning policy and practice together with perspectives on the implications of the EU Water Framework Directive for the management of diffuse urban surface water drainage and stormwater wetlands. Appendix D provides information on general discharge standards and consents for surface waters and details of the structure of existing receiving water quality classification within England & Wales. A brief outline is also given in Appendix D of sediment quality standards which might be appropriately applied as "limit" loadings for the contaminated sediment which accumulates within urban stormwater wetland systems.

The only effective means of ensuring the protection of urban receiving waters is through SuDS firstly minimising the polluting load through best environmental practice (i.e reduce at source) and subsequently minimising the discharge of polluting material (through appropriate and effective mitigation measures to deal with unavoidable levels of contamination

6.2 SuDS and the EU Water Framework Directive

6.2.1 Objectives and key elements

The implementation of the EU Water Framework Directive (WFD) has major consequences for the protection of the aquatic environment including urban wetlands. It will require the UK to produce integrated catchment-based plans for dealing with diffuse pollution sources, including those generated within urban areas The key objective which is relevant to wetlands as set out in Article 1 of the Directive is :

- the protection, restoration and enhancement of the status of aquatic ecosystems and associated wetlands

The emphasis placed on diffuse pollution in the WFD is of particular relevance to the problem of urban surface water drainage. Whilst the Directive does not define diffuse pollution, it does specify the need to address the problems as follows:

- Article 11.3(h); "*for diffuse sources liable to cause diffuse pollution, measures to prevent or control the input of pollutants*" are required

6.2.2 Diffuse urban pollution and river basin management planning

A key requirement within the WFD under Article 16 will be the production of River Basin Management Plans (RBMPs) which are the main mechanism of achieving the Directive's environmental objectives. RBMP's for a particular river basin should include:

- definition and characteristics of the river basin (by end of 2003)
- environmental monitoring data and consultation in preparation of RBMPs (to commence by end of 2006)
- details of the environmental impacts of human activity, including information on diffuse pollution sources, magnitudes and trends (by end of 2004)
- interim overview of River Basin District (RBD) water management issues (end of 2007)
- strategic plans for the achievement of "*good status*" within RBDs to be specified within the Programme of Measures (by end of 2009)

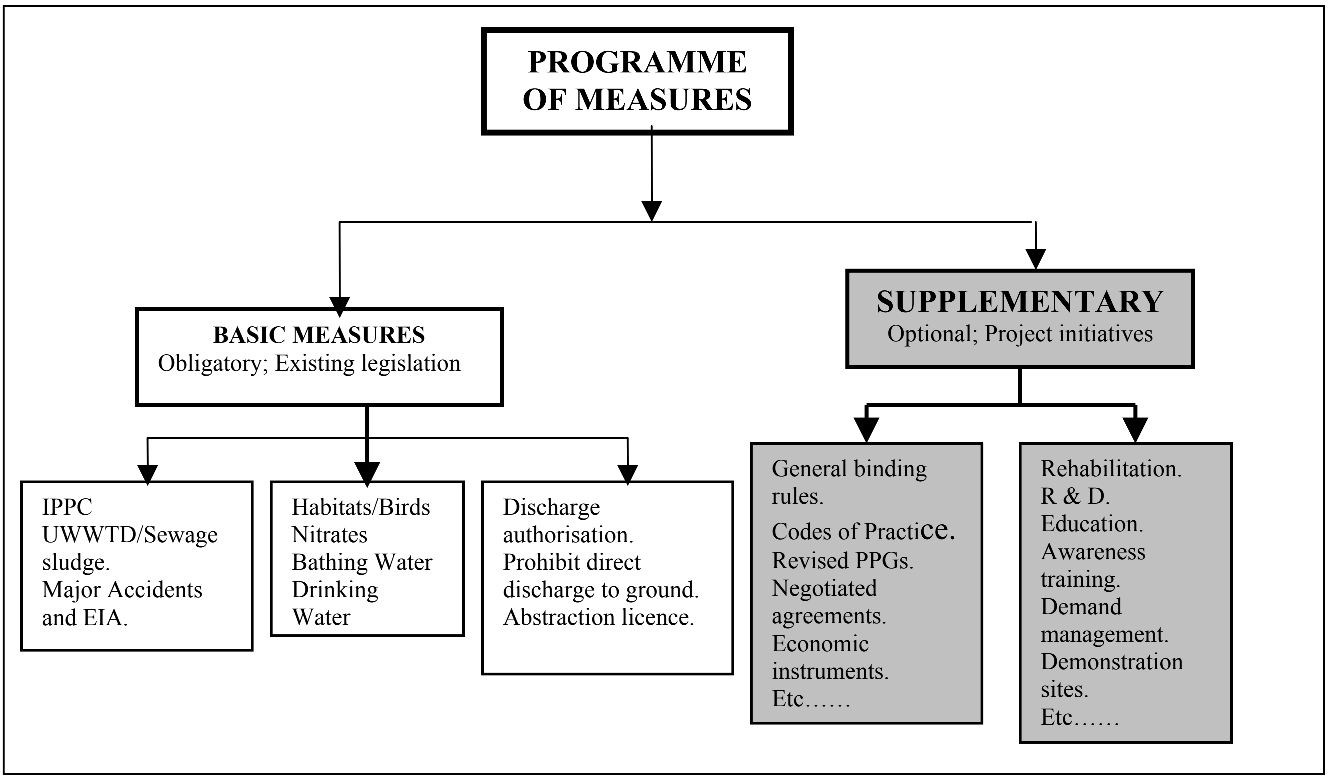


Figure 6.1 RBMP Programme of Measures

Once monitoring has determined waterbody status within a RBD, the competent authorities must then use this information to develop an integrated Programme of Measures. Figure 6.1 illustrates the structural requirements for such a programme.

6.3 Implementing SuDS within River Basin Management Planning

6.3.1 Prohibition notice policy

It is standard UK regulatory policy (within the Agency, SEPA and the N Ireland E & HS) not to seek formal consents for urban surface water discharges. Both the Agency and SEPA are committed to the promotion of source control and passive treatment such as urban wetlands as best management practice in their response to Strategic and Local Plans. Normal regulatory practice therefore, is to rely on planning conditions and building warrants as the means of delivering best practice. Where source control, passive treatment or engineering measures such as oil separators are agreed with the discharger, Conditional Prohibition Notices can be served. SuDS structures can then be made a condition of the Notice.

6.3.2 Planning and partnership approaches

SuDS Implementation and the Planning Process
The planning system and local authorities are in a key position to bring about change and play a major role in controlling and influencing the decision-making process on land use activities. They can work within relevant development, structure and local plans as well as the AGENDA 21 process to encourage and introduce appropriate design guidance and community planning. However, planners can be faced with conflicting consultation responses on SuDS from statutory consultees causing serious difficulties for the planning process

The revised (July 2001) DETR PPG 25 "*Development and Flood Risk*" specifically refers to surface water drainage and SuDS which should be helpful in this dialogue between the Agency and Planning Authorities.The revisions have strengthened and sharpened the precautionary risk-based focus of the guidance to ensure a stronger emphasis on planning in relation to river catchments at all stages in the plan-making process.

SuDS Implementation and Developers
Developers are becoming more familiar with, and more willing to consider, SuDS construction. They will construct what is necessary, providing the appropriate design requirements can be taken account of when negotiating the land purchase price. However, they tend not to consult with the Agency until after land purchase and they are consequently reluctant to accept drainage solutions which might reduce the number of development units. Delays caused by disagreements between the Agency, the Water Companies and the Highways Agency (and/or County/District Highway Authorities) are also a frequent cause for complaint. For smaller developers, clear SuDS design specifications and experienced consultants is a particular problem. Closer liaison and interaction between the regulatory authorities and the UK House Building Federation might help to facilitate a better understanding of the major issues.

SuDS Implementation and the Water Companies
Water Companies are another important target group and discussion Workshops/Seminars might provide effective fora for airing Agency concerns.

It is not clear however, to what extent such initiatives would be welcomed by the Water Companies and it may be more effective to provide training and support for Agency staff involved with routine discussions about sites. Nevertheless, the water companies generally are becoming increasingly committed to source control approaches which seek to divert and control rainfall-runoff at source

> **Surface Water Source Control: Policy Statement**
> July 1998. Thames Water
> - seek to ensure that new connections to the public sewerage system do not pose an unacceptable threat of surcharge, flooding or pollution
> - with advice from DETR, we will encourage ....sustainable infrastructure development which does not involve discharge to the public sewerage system.
> - we recognise that it is preferable to use locally available watercourses, with attenuation or soakaways to drain the surface water runoff from sites.

SuDS Implementation and Highway Drainage
Planning legislation allows the Environment Agency to make representation opposing development projects (including new or improved highways), which are likely to have an unacceptable impact upon the aquatic environment, and Planning Policy Guidance (PPG) 12 provides background information on pollution prevention and surface runoff control.

To date, the Highways Agency have been cautious in their approach to the use of vegetated treatment systems for the control and management of highway runoff. However, the new Advice Note covering this theme within the new update to Section 2 (Drainage, HA 103/01), Volume 4 of the DMRB may help to promote wetland systems. A recent publication by the Institution of Highways & Transportation (2001) also recommends SuDS best practice structures for the control and management of road and highway runoff and provides more detail on their relative benefits over conventional gutter-kerb-sewer drainage systems.

SuDS Implementation and Stakeholder Partnerships
Under the Water Framework Directive, the evolution of water resource management towards an eco-centric, holistic approach to catchment management requires the sharing, coordination and integration of objectives, values and inputs from a broad range of agencies, public and other organisations when conceiving, designing and implementing policies, programmes or projects. In particular, local community interest and general public support will be crucial in achieving the goals of integrated urban catchment management under the Directive. Partnership approaches involving representatives of all stakeholder organisations (regulatory authority, water utilities, local authorities, house builders, developers, government and NGOs) have been successful within the Scottish SuDS Working Party in implementing best practice technology for urban stormwater management

It is necessary to raise the profile of urban surface water drainage and its environmental consequences and to run education and training programmes on the potential of SuDS best practice. Where the issues of surface water become understood and appreciated, there is considerable potential for a more collaborative and partnership approach to future catchment policy development. Inevitably there is a difficult balance to be sought between the regulatory lead role that the Environment Agency must take, and the collaborative process which must subsequently develop, in order for a more sustainable approach to be achieved.

7. DECISION SUPPORT APPROACHES

7.1 Introduction: Towards a Multi-Criteria approach

Sustainability criteria for urban wetlands must be similarly referenced against those parameters related to all three elements of the SuDS triangle; water quantity, water quality and amenity. Thus, design and construction, environmental/ecological impact, operation and maintenance, health and safety, social/urban (community/amenity) and economic issues become prime potential sustainability criteria to facilitate comparisons and accreditation of drainage options with regard to capital cost, resource use, acceptability, performance, maintenance etc. It is appropriate, if not necessary, to evaluate the sustainability of urban wetland systems against multi-criteria and multi-objectives placed within an overall subjective decision-support framework.

7.2 Defining Primary Criteria, Indicators and Benchmarks

Table 7.1 outlines a possible listing of primary generic criteria which could be applied as basic sustainability indicators for urban wetland SuDS. It also identifies a range of secondary indicators and benchmark "standards" against which a specific wetland or other SuDS structure or set of drainage options might be assessed. The listing could also provide a suitable basis for developing holistic accreditation criteria for assessing the relative sustainability of any existing urban wetland or other SuDS structures as well as providing a basis for post-project evaluation of sustainability gains achieved following the introduction of a SuDS initiative within an urban development.

7.3 Applying a Multi-Criteria Approach

Once the objectives of a specific scheme have been identified as a basis for a decision on the adoption of varying drainage options for an urban development (or re-development in the case of a retrofitting design), the multi-criteria approach can be implemented as illustrated in Figure 7.1

7.4 Benchmark Indicator Standards

Long term performance, health and safety together with O&M requirements are prime benchmark indicators which need to be much more fully determined before the sustainability of urban wetlands or other SuDS structures can be championed in an unqualified manner The Environment Agency in conjunction with HR Wallingford, has established a national database Internet site (www.suds-sites.net) which will complement the more detailed US EPA national database already available on the web (www.bmpdatabase.org).

Table 7.1 Sustainability Criteria and Indicators for Urban Wetlands and SuDS

Category	Primary Criteria	Secondary Criteria	Possible Benchmarking Standards
Technical and Scientific Performance	• System performance (Quantity and Quality) • System reliability • System durability • System flexibility and adaptability	• (i) Storage and Flooding (ii) Receiving water quality • Performance reliability, failure, health and safety • Design life • Capability for change over time including retrofitting	• (i) Design storm return interval (RI) storage volume; No. of floods per year and/or properties affected; Downstream protection value; Disruption time/costs (ii) Pollutant concentration probability exceedance; Firstflush capture potential (10/15mm effective runoff treatment for all storms); %age compliance with RQOs/consents etc.; No. of complaints; %age storm events captured for treatment; Pollutant degradation rates • %age pollutant removal; In-basin quality and health risk (eutrophication, odorous sediment, stagnant water , bacteriology etc..); Likelihood/risk of failure; Operational safety • Operational lifetime (storage volumes; sediment accumulation rates) • Design freeboard (storage and water quality); Costs and ease of retrofitting and/or add-on structures and features
Environmental Impacts	• Water volume impact • Water quality impact • Ecological impact • Resource use • Maintenance, servicing provision and responsibilities	• Flooding • Pollution control • Habitat and ecological diversity • (i) Land use (ii) Material use (iii) Energy use (iv) Chemicals • O & M requirements	• Drawdown times; Dilution ratios; Downstream erosion; Frequency of by-pass operation • Treatment retention times; Litter/Gross solids; RW RE classification; Compliance with RQO and receiving water (RW) standards; Maintenance of lowflow status • RW BMWP/ASPT scores; No. of key species and alien species introduced; SuDS ecological and conservation status (total flora/fauna); role in BAPs; PYSM eco-quality assessment • (i) Land take (area/cost); No. and value of development units lost (ii) Aggregates/concrete/top-soil/appurtenances use and costs (iii) Construction/O & M energy consumption (iv) On-site herbicide/pesticide applications • Need and frequency for O & M servicing to maintain technical/environmental/amenity/habitat objectives • Need for monitoring (water quality, plant health etc)
Social and Urban Community Benefits	• Amenity; aesthetics, access and community benefits • Public information, education and awareness • Stakeholder acceptability (perception and attitudes of risks and benefits) • Health and safety risks	• Social inclusion • Public awareness and understanding • Perceived acceptability and impacts • Risk audits	• Community benefits (assessment of amenity--boating/fishing/recreation; access; aesthetics); No. of visits; Quality of life enhancement; Population and groups served • Information provided (Interpretation boards; visitor centres; signage); Knowledge in local community; Ranger service/Voluntary group participation; Demonstration site use • Willingness-to-adopt; Assessment of %age concerns (health/safety); Assessment of %age improvements gained; Awareness of risks • Probability of infection and safety risks; risk exposure audits; service/amenity outage times
Economic Costings	• Life cycle costs • Financial risks • Affordability	• Investment and operational costs • Risk exposure • Long term affordability	• Design, capital, O & M and maintenance costs; Disposal and decommissioning costs; Other material and production costs • C/B Analysis; Investment loss risk; Site reclaim value • Adoption and liability costs/risks; Amenity income streams (willingness-to-pay); Long term amenity costs • Economic add-on value (enhanced land/property values)

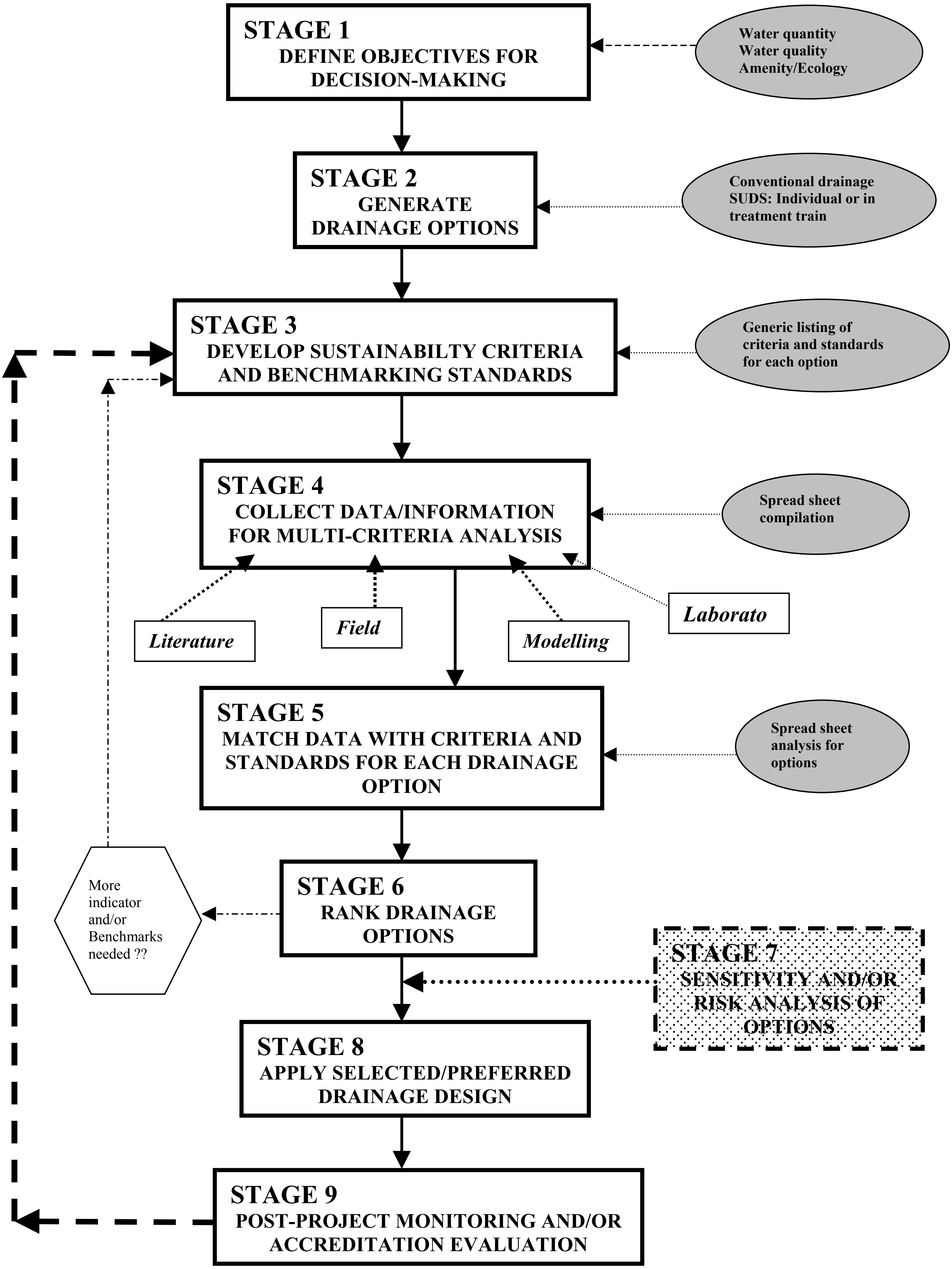


Figure 7.1 Multi-Criteria Analysis for the Evaluation of Urban Runoff Control and Treatment Options

7.5 Matrix Approaches

Table 7.2 SuDS Technology Evaluation Matrix

Criterion	Infiltration Systems	Porous Paving (with reservoir structure)	Grass Swales	Grass Filter Strip	Wet Retention Basins	Constructed Wetlands
Planning cost (Pre-planning and design)	+	o	+	o	+	-
Construction cost (Capital investment)	+	o	+	o	-	o
O & M cost (Including personnel, plant replacement and sediment disposal)	+	+	o	+	o	o
Technical implementation effort (excavation, lifetime O & M, decommissioning)	+	o	+	+	-	o
Water re-use (not including groundwater recharge)	-	-	-	-	+	+
Whole-life cost (Duration, affordability, flexibility for retrofitting etc)	+	-	+	+	+	o
Reliability against Failure (Forced and planned outage during lifetime)	-	o	+	+	+	o
Planning and Practical Experience (System performance knowledge)	o	+	o	-	+	-

KEY:
\+ more advantageous as compared to other technologies
o neither advantageous nor disadvantageous as compared to other technologies
\- less advantageous as compared to other technologies

A comparative matrix approach which includes sustainability referencing for various types of SuDS stormwater treatment systems is given in Table 7.2. This type of multi-matrix approach is primarily intended for general planning support in the pre-selection of integrated urban BMP systems and cannot be used for detailed design. Although wetlands may have the possibility of water re-use, there may be an overall water loss as a result of plant evapotranspiration during the summer period in comparison to an unvegetated open water system such as a wet retention pond.

Table 7.2 suggests that wetlands generally seem to be neutral in terms of advantages and disadvantages over other SuDS systems, the gains in performance and environmental capacity as well as in potential community benefits more than compensate for any technical shortfalls

7.6 Wetland design procedure

Figure 7.2 presents a general process diagram for the design procedure and flow of required inputs and considerations at differing stages of design, implementation and operation. The inclusion of amenity/recreation as a separate sub-set within the process diagram reflects the fact that some wetland systems, such as those intended for highway runoff (and perhaps some developed within industrial zones), will not have need to recourse to such criteria

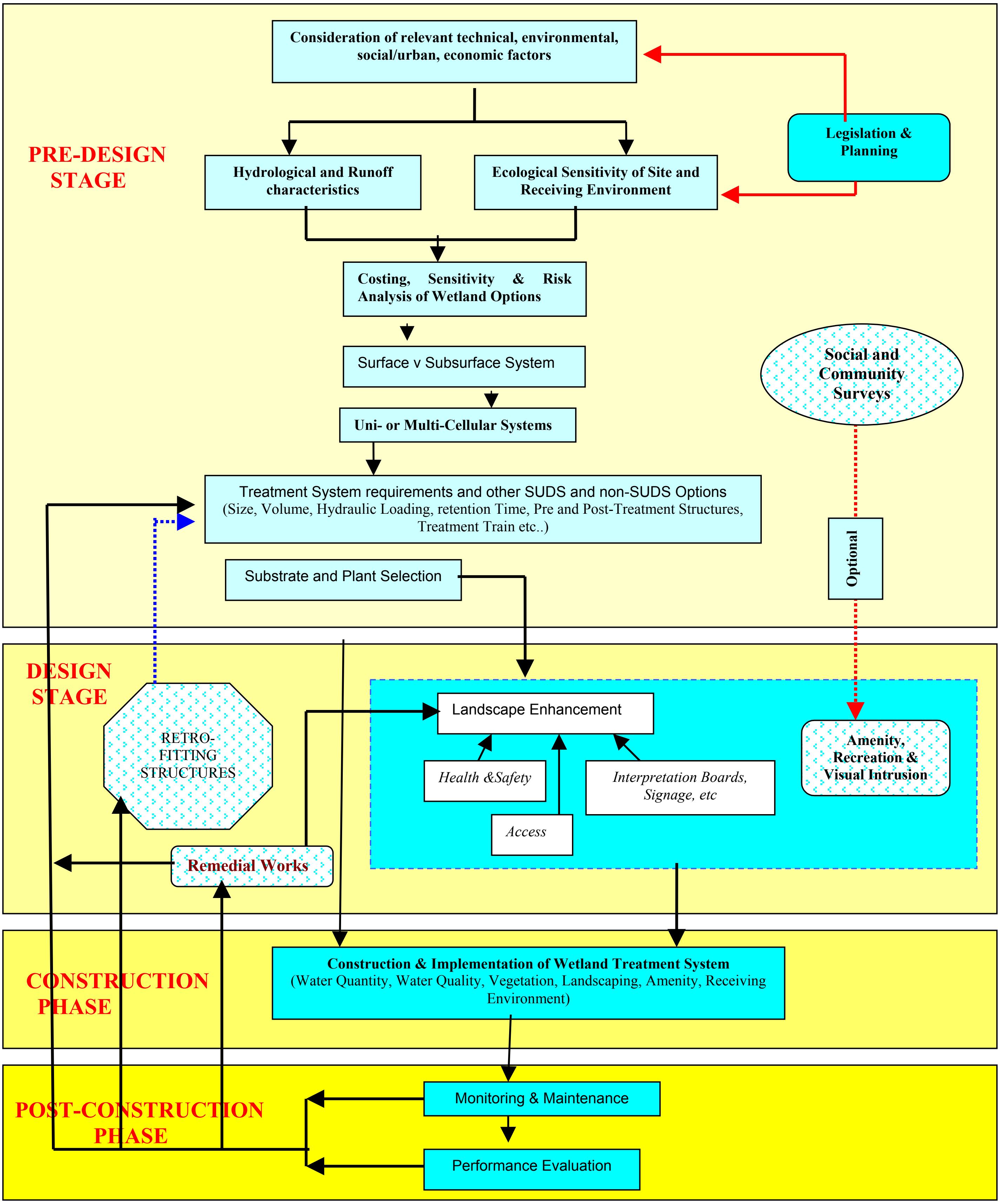


Figure 7.2 Process Diagram for the Design of Constructed Wetlands

8. RECOMMENDATIONS FOR FURTHER RESEARCH

8.1 Introduction

The suggestions for further work which are given below are not prioritised but are grouped into thematic issues.

8.2 Database and Monitoring

- Development of national and standardised database for urban wetlands as part of national SuDS monitoring.

- Development of national water quantity and water quality monitoring programme for differing types and locations.

- Full scale field evaluation and revisions of decision-support approaches for urban wetland design and accreditation.

- Identification of selected national demonstration sites; to be developed in conjunction with developers, British House Building Federation etc.

8.3 Operational Evaluation

- The evaluation of long term performance and cost-effectiveness of differing urban wetland SuDS.

- Evaluation of long term effects of below-surface pollutant infiltration from wetlands to groundwater.

- The evaluation of urban wetland pollutant removal efficiencies; robust modelling procedures for the dynamic nature of wetland flows and mixing processes.

- Development of operational and maintenance handbooks and inspection routines for urban wetlands.

8.4 Pollutant Pathways

- Hydrocarbon chemical and microbial degradation; sediment and plant uptake.

- Metal uptake and food chain transfer.

- Pesticide degradation and plant uptake.

- Bacterial and pathogen pathways, exposure, degradation and resuscitation and uptake rates in sediment, plants, insects, invertebrates, birds and other wildlife.

8.5 Wetland Design and Management

- Techniques for first-flush treatment; role of wetlands in inner urban areas and in conjunction with conventional drainage systems.

- Issues of wetland adoption, liability including issues of long term wetland management and multi-party agreements.

- Public attitudes and behavioural surveys of local/community uses of, and needs for, urban wetland systems.

- Wetland design for the removal of priority pollutants including methyl tertiary butyl ether , hydrocarbons, pesticides, bacteria/pathogens, oestrogens etc.

8.6 Life-cycle Assessment

- Whole life-cycle costing for urban wetlands, including MIPS (**M**aterials **I**ntensity **P**er **S**ervice Unit) analysis; (as part of national SuDS monitoring

- Identification of separate land take, resource/energy use and O & M costs for differing urban wetland types.

- Identification and quantification of sedimentation rates for urban wetland environments.

- Identification of plant replacement requirements, frequency and costs.

8.7 Wildlife/Amenity & Social/Urban Issues

- Issues related to wetland naturalisation and species colonisation

- Food chain transfer and resultant effects of differing pollutants.

- Issues of fish management in urban wetlands.

- Health hazards posed to wildlife and the public from exposure to urban wetland pollutants such as bacteria/pathogens, hydrocarbons etc.

- Public attitudes to wildlife and ecological issues associated with urban wetlands and means of combating vandalism.

KEY DOCUMENTS

Bray, R.J. 2001. Maintenance of sustainable drainage: Experience on two EA demonstration sites in England. 93 – 104 in Pratt, C J., Davies, J W and Perry, J L (Edits); *Proceedings 1st National Conference on Sustainable Drainage*, June 2001, University of Coventry, Coventry.

CIRIA. (Hall, M J., Hockin, D L and Ellis, J B) 1993. *Design of flood storage reservoirs*. Butterworth-Heinemann (also CIRIA), London.

CIRIA. (Nuttall, P M., Boon, A G and Rowell, M R) 1997. *Review of the design and management of constructed wetlands*. Report 180. Construction Industry Research & Information Association, London.

CIRIA. 2000a. *Sustainable urban drainage systems: A design manual for Scotland and N Ireland*. Report C521, Construction Industry Research & Information Association, London.

CIRIA. 2000b. *Sustainable urban drainage systems: A design manual for England & Wales.* Report C522, Construction Industry Research & Information Association, London.

CIRIA. 2001 *Sustainable urban drainage systems: Best Practice Manual*. Report C523, Construction Industry Research & Information Association, London.

Cooper, P F., Job, G D., Green, M B and Shutes, R B E. 1996. *Reed beds and constructed wetlands for wastewater treatment*. WRc, Swindon.

DETR. 2001. *Achieving a better quality of life: Review of progress towards sustainable development*. Department of the Environment, Transport and the Regions, HMSO, London.

Ellis, J B and Revitt, D M. 1991. *Drainage for roads: Control and treatment of highway runoff*. Report NRA 43804/MID.012, National Rivers Authority, Reading.

Halcrow Group Ltd & Middlesex University. 1996. *The design and performance of vegetated treatment systems for highway runoff, literature review and feasibility study*. Halcrow Group Ltd & Middlesex University, Urban Pollution Research Centre, Environment Agency Thames Region, Reading.

Halcrow Group Ltd & Middlesex University. 1998. *Treatment of highway runoff using constructed wetlands: An interim manual*. Halcrow Group Ltd & Middlesex University, Urban Pollution Research Centre, Environment Agency Thames Region, Reading.

Halcrow Group Ltd & Middlesex University. 2003. *Protection of the water environment using balancing facilities.* Final Report, Halcrow Group Ltd & Middlesex University, Urban Pollution Research Centre, Environment Agency Thames Region, Reading.

Highways Agency, 2001. *Vegetative treatment systems for highway runoff. In; Design Manual for Roads and Bridges* Vol 4 Section 2. Highways Agency, Scottish Executive Development department, National Assembly for Wales, Dept for Regional Development, Northern Ireland

Hydraulics Research, 2001. *Guide for the Drainage of Development Sites.* R&D project report SR574

Institution of Highways & Transportation. 2001. *Guidelines for the environmental management of highways*. Institution of Highways & Transportation, London.

IWA. 2000 *Constructed wetlands for pollution control: Processes, performance, design and operation*. (Eds; Kadlec, R H., Knight, R L., Vymazal, J., Brix, H., Cooper, P and Haberl, R). Scientific & Technical Report No.8., IWA Publishing, London.

Kadlec, R H and Knight, R L. 1996. *Treatment wetlands*. CRC Press, Lewis Publishers, Boca Raton, Florida, USA.

Kadlec, R H. 2000. The inadequacy of first-order treatment wetland models. *Ecological Engineering*, 15, 105 - 119.

Merritt, A. 1994. *Wetlands, Industry and Wildlife: A manual of principles and practices*. The Wildfowl & Wetlands Trust, Slimbridge, Gloucs.

Middlesex University, Urban Pollution Research Centre (2003*) Constructed Wetlands and Links with Sustainable Drainage Systems.* Environment Agency Technical Report *P2-159/TR1.*

US Environmental Protection Agency. 1998. *Free water surface flow constructed wetlands for wastewater treatment and wildlife habitat: A technology assessment*. EPA/832-R-99-006. Office of Water, USEPA, Washington, DC.

APPENDIX A

WETLAND PROCESSES

1. Sedimentation

This is the (solid-liquid) separation process which uses gravitational settling to remove silt and suspended solids and is considered to be the predominant mechanism for the removal of many solid-associated pollutants from the water column. Assuming that complete mixing occurs during a storm event and that sedimentation is the dominant removal process, it is possible to derive for any given discharge a first-estimate of the required wetland volume and the percentage solids retention. Figure A1 shows that solids capture increases the smaller the event discharge (Q) is relative to the basin volume (V). Solids retention also increases as the inflow suspended solids concentration (C_{in}) increases relative to the background concentrations (C_{pr}). The individual curves refer to the ratio of inflow solids concentrations (C_{in}) to assumed background concentrations immediately preceding the storm event (C_{pr}).

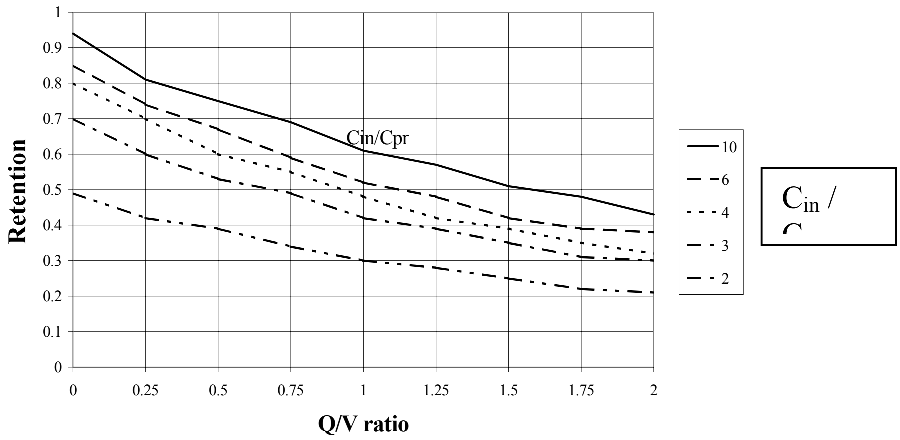


Figure A1. Solids Retention Under Differing Discharge and Volume Conditions.

Sedimentation rates in wetland systems following a storm event will be at least equivalent to those experienced in wet retention basins and first order settling rates can be determined from consideration of particle settling velocities using procedures such as outlined in Hall *et al* (1993) for flood storage detention basins. A procedure for calculating the settling velocity of coarse and fine particulates is given in Appendix B. Based on available data, it is possible to draw up a series of percentage solids v time retention curves for typical dry weather periods (or inter-storm intervals) as indicated in Figure A2 which illustrates typical capture curves for three wetland basin sites in S E England. It is evident that for all three sites, between 50 - 60% of the total suspended solids load can be expected to be removed within 5 days following most storm events with more than

Required Wetland Volume
The computations shown in Appendix A and the retention curves of Figure 5 can help to reach decisions on required wetland volumes (V) for a particular location by multiplying the retention time (HRT or t_{ret}) by the daily flow (Q_d ; m^3/d):

$$V = t_{ret} \times Q_d$$

to achieve a desired target level of solids reduction (and for any required sediment grading threshold)

70% of particles greater than 0.5mm being settled out. With the enhanced sedimentation enabled by vegetative biofiltration, it is evident that stormwater wetlands are fully capable of achieving satisfactory solids removal efficiencies.

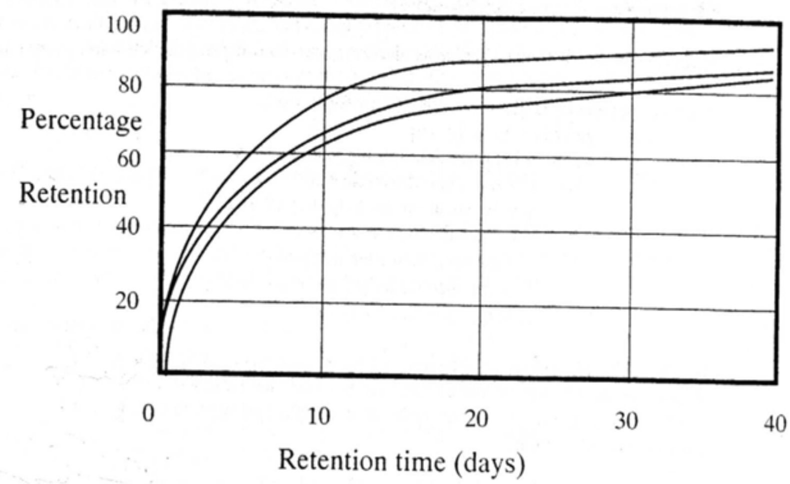


Figure A2. Solids Time Retention Curves for Three Wetland Sites

In wetlands having a significant biofilm mass, particles of less than 4-5 μm are unlikely to coagulate and may stay in stable suspension. Apart from retention time, the most significant factors affecting solids settling are emergent plant densities, turbulence, inlet-outlet conditions and water depth. Adverse flow conditions can be minimised by promoting sheet flow conditions into the wetland. The use of inlet distribution weirs or surface filter strips in SF wetlands or gabion blocks for SSF systems can provide efficient inlet flow distribution (Ellis, 1990). Uniform flows distributed evenly across the wetland macrophyte zone will reduce chanellisation and short-circuiting and enhance sedimentation rates as well as encourage the retention of the finer clay size particles (Lawrence and Breen, 1998).

Re-mobilisation of pollutants from oxygen-deficient benthal sediment may still occur as a result of the disturbance of bacterially decomposed organic matter deposited after storm events. Fine sediments either in suspension in the water column or re-suspended from the bed, may be flushed out when relatively clean stormwater enters the basin during a large storm event. The cleaner stormwater inflow displaces the more turbid wetland water, causing a net export of contaminated sediment. Microbial activity under reducing or anaerobic bed conditions can also release soluble pollutants (phosphate, nitrogen, heavy metals, ammonia) into the overlying water column and thus reduce the overall retention performance. In addition, bioturbation and benthic organism excretion can also release heavy metals into the overlying water column. Such re-mobilisation processes can be offset by increasing the wetland area or by cycling the wetland outflows through an open water zone (or further wetland cell) to take up the released nutrients and organic compounds. Whilst the underlying substrate may remain anoxic, the sediment-water interface layer is likely to be re-oxidised by both natural drawdown and recharge between and during rainfall events.

In gravel bed wetland systems, solids accumulation and associated biofilm development can impede influent contact with both the macrophyte roots and the underlying media especially adjacent to the inlet where most sedimentation occurs.

Efficient inlet distribution (e.g using gabions) and carefully selected washed gravel media sizes can help to alleviate this problem. Where metal removal is a key water quality objective, mixing with coarse organic soil may be appropriate, although it should be noted that introduced weeds are likely to be present and can cause later problems.

2. Adsorption

Adsorption of pollutants onto the surface of suspended particulates, sediments, vegetation and organic matter is a principal mechanism for the removal of dissolved and colloidal pollutants such as nutrients, bacteria and the more soluble metal species as well as the more toxic polyaromatic hydrocarbons. As much as 70 - 90% of these pollutant groups can be associated with the fine particulate and colloids in stormwater runoff. Adsorption occurs as a result of electrostatic and physical forces as well as chemical reactions. Adsorption rates under sustained or attenuated loading conditions such as encountered with urban stormwater flows, are considered to be inversely related to the particle size and directly related to the organic matter content.

> **Adsorption Behaviour of a Pollutant**
> The balance or *equilibrium* between the solid-associated (C_s, sorbed) and dissolved (C_w) phases of a pollutant is commonly referred to as a *sorption isotherm*. The expression used to describe this pollutant *partitioning* or adsorption relationship is known as the *Freundlich isotherm*:
> $$C_s = K.\, C_w^{\,n}$$
> where K is the Freundlich constant (or pollutant adsorption coefficient) and n is a measure of deviation from linearity. A value of n = 1 reflects those situations in which the attractiveness of the solid for the sorbate remains the same for all levels of C_s. This linear isothermal relationship usually only applies over narrow ranges in C_w particularly at low pollutant concentrations. The distribution ratio (K_d) of total pollutant equilibrium concentrations in the sorbed and dissolved phases is expressed as:
> $$K_d = C_s / C_w$$
> $$\text{and hence; } K_d = K.\, C_w^{\,n-1}$$

Adsorption processes are therefore enhanced by increasing the contact of the surface runoff with the wetland mineral substrates and with the vegetative surfaces and plant detritus which provide large surface areas for adsorption. In addition, high retention times, shallow water depths and an even distribution of influent will further enhance the interactions of the stormwater with substrate and plant surfaces thereby increasing the adsorption potential. The macrophyte substrate and associated biofilm comprise essential treatment zones for colloidal and dissolved pollutants with organic carbon uptake rates being in the order of 0.2 - 1.2 g/m^2/day for a typical urban runoff wetland system (Cooper *et al*., 1996). This compares well with the uptake rates reported for trickling filters and maturation ponds which range between 0.14 - 0.96 g/m^2/day (Metcalf & Eddy Inc, 1991). The biofilm is particularly susceptible to scouring during storm events and thus the wetland should be designed to limit velocities within the macrophyte zone which ideally should be less than 0.3 - 0.5m/s.

> **Maximum Inflow Velocity**
> The expected maximum velocity (U_{max}; m/s) in the wetland can be calculated as a function of the peak flow rate (Q_{pkmax} ; m^3/s) and wetland surface area (A_s; m^2) as: $U_{max} = Q_{pkmax} / A_s$

3. Precipitation and dissolution

Many ionic species such as heavy metals dissolve or precipitate in response to changes in the solution chemistry of the wetland environment. Microbial oxidation and precipitation in the wetland substrate fix metals such as cadmium, copper, lead, mercury and zinc as insoluble sulphides under the reducing conditions commonly found in wetlands. Fulvic and humic acids released by decaying organic matter can also form complexes with metal ions.

4. Filtration

Enhanced filtration occurs in most wetlands as a direct result of reduced velocities brought about by the hydraulic resistance of macrophyte roots, stems and plant tissue. Such biofiltration is most effective when inflow velocities are below 0.5 m/s and flows are distributed uniformly across the width of the bed. A dense vegetation cover can also be very effective at removing gross solids, litter and floatable material from the incoming stormwater flows. Further pollutant filtration will also occur within the soil matrix of the wetland substrate.

5. Biochemical interactions

Vegetative systems possess a variety of processes to remove nutrients and other pollutant material from the water column. In general, these processes include high plant productivity (a large biomass), decomposition of organic matter, adsorption and aerobic or anaerobic microbial mechanisms. Through interactions with the soil, water and air interfaces, plants can increase the assimilation of pollutants within a wetland system providing surfaces for bacterial growth and adsorption, filtration, nutrient association and the uptake of heavy metals, hydrocarbons etc. Various studies have demonstrated the efficiency of pollutant removal following contact with the macrophyte rhizosphere (Cooper *et al*., 1996).

Two principal biochemical processes operate to immobilise heavy metals in plant tissue following uptake; (i) complexation by free ions in root cell walls and, (ii) enzyme-mediated incorporation into shoot tissue. There is some evidence that aquatic macrophytes have genes providing a toxic tolerance which enables considerable plant metal accumulation to occur without interfering with vital metabolism processes. Plant uptake of these pollutants provides temporary removal of metals, nutrients and hydrocarbons from the sediments, allowing renewed adsorption sites within the sediment for the attraction of other ions. Heavy metals and low level (<1 mg/l) concentrations of soluble inorganic phosphorus are readily immobilised in neutral mineral soils by adsorption e.g on clay minerals and precipitation reactions e.g with aluminium and iron. As adsorption-precipitation phenomena are partially reversible, this process cannot be assumed to be a permanent sink for phosphorus or metals and incoming dilution water can for example, cause phosphorus release from the sediments into solution.

Pollutant Decay in Wetlands

The reduction achieved in pollutant concentrations across a constructed wetland can be related to a first-order kinetic relationship:

$$C_{out} = C_{in} \text{ x } \exp^{-kt}$$

where pollutant concentrations in the inflow and outflow are C_{in} and C_{out} respectively; k is the reaction rate constant and t is the Hydraulic Retention Time (HRT). For an unrestricted SF wetland flow system, HRT = lwd / Q_{av}.

6. Volatilisation and aerosol formation

Evaporation and volatilisation can remove the most volatile pollutants such as ammonia, chlorinated hydrocarbons and some surface oils from wetlands. Air and water temperature, wind speed, subsurface agitation and particularly the existence of surface films can affect the rate of volatilisation. Aerosol formation may also play a minor role in removing wetland pollutants but only during periods of persistently strong winds.

7. Infiltration

For wetlands having underlying permeable soils, pollutants may be removed through direct infiltration to ground and may eventually reach the permanent groundwater level. Percolation through the underlying soil matrix will provide physical, chemical and biological attenuation depending on the matrix depth, particle size, organic content and degree of saturation. Whilst wetland recharge is unlikely to lead to groundwater contamination it should be avoided wherever possible by the use of an impermeable bed (clay or clay bentonite mixtures) or artificial (PVC or HDPE) liners.

Additional References

METCALF and EDDY INC. 1991. *Wastewater engineering: Treatment, disposal and reuse*. 3rd Edition, McGraw Hill, London.

APPENDIX B

WETLAND POLLUTANT EFFICIENCY RATES

1. Introduction

A full procedure for estimating the pollutant retention efficiency of a wetland basin as a function of particle size is given in Section 6.5 (pages 89 - 95) in the CIRIA manual "*Design of Flood Storage Reservoirs*" (Hall *et al*., 1993). A simplified modification of the procedure is presented here (in the form of a "look-up" table), with the emphasis being placed on solids retention.

2. Particle Settling Velocity

As a design guide, Table B1 provides values of fall velocity (Vs) for a typical range of particle diameters. The settling velocity (Vs) values in Column 3 assume a density (or specific weight) equivalent to common quartz (2.65) for all particle sizes. However, for particles less than 0.1mm (very fine sand), the density actually

Table B1. Solid Sizes and Settling Velocities

Solids Grade	**Particle Diameter** (d; mm)	**Settling Velocity** (Vs; mm/s at 10^o C) Density; 2650 kg/m^3	**Density** (kg/l)	**Sedimentation Efficiency** (%)
Pea Gravel	10.0	800.0	2.65	100
Coarse sand	1.0	200.0	2.65	95
Medium sand	0.5	70.0	2.5	90
Fine sand	0.2	22.0	2.5	90
Very fine sand	0.1	10.0	2.5	90
Coarse silt	0.05	6.7	2.3	80
Medium silt	0.01	0.18	2.0	70
Fine silt	0.005	0.016	1.7	60
Clay (and organics)	0.001	0.011	1.1	50

reduces quite sharply which reduces the sedimentation efficiency of such small relatively buoyant particles. In addition, even small eddies and currents induced by flow, wind or thermal gradients in the wetland will exacerbate this buoyancy as will short-circuiting. The sedimentation efficiency loss is therefore highest for the finest silt and clay gradings as can be seen from inspection of the final two columns in Table B1. It should be noted that Table B1 assumes an ambient temperature of 10^o C, but as temperature increases the kinematic viscosity and density decrease which in turn lead to an increase in the settling velocity. Thus the retention efficiency values quoted in Table B1 are on the conservative side for most UK weather conditions.

3. Solids Retention

The total solids retention of the wetland basin can be estimated as :

Retention (%) = Σ[Fraction (%) x {1 - e (-Vs.t / d)}] where Vs is the fall velocity (m/s), t is time in seconds and d is the average wetland depth.

Solids retention for individual size ranges for any specific time period (say 0.2, 0.5, 0.8, 1.2……n days) can be estimated as:

Retention = γ_n / γ_0 = 1 - 1/ [{1 + (10n.Vs.As/Q)}]
where γ_n and γ_0 are the solids concentrations after 1 day, t_n and start time, t_0 respectively; Vs is the settling velocity (m/d); As is the wetland surface area, (ha x 10^4 m^2); Q is the (post-storm event) average dry weather flow rate (Ml/d x 10^3 m^3/d); and n is the sedimentation basin performance coefficient. Given the shallow depth and potential for significant inflow eddy currents within constructed wetlands, their sedimentation efficiency rating (especially for particle sizes below 80 μm), appear to be relatively poor (n = 0.5) to very poor (n = 1). The interception equations for these differing sedimentation conditions would thus be of the form:

Very Poor: γ_n / γ_0 = 1 - 1/ (1 + {10Vs. As/Q})
Poor: γ_n / γ_0 = 1 - 1/ (1 + $\{10Vs. As/Q\}^2$)
Excellent: γ_n / γ_0 = 1 - e (10Vs. As/Q)

The cumulative solids retention is then given by:

Cumulative Percentage Retention = Σ[Fraction (%) x (1 - γ_n / γ_0)]

4. Solids-Retention Curves

Based on particle size analysis of solids discharged to a wetland over specific time periods during and following a storm event, it is possible to compute a site-specific "solids-time" retention curve as illustrated by Figure A1(Appendix A). The procedure can be shortened by taking a few key size groups from Table B1 e.g coarse sand, fine sand and clay. The procedure can also be improved by direct laboratory determination of the settling velocities rather than using the Vs values given in Table B1. A procedure for empirically determining Vs is given in Hall *et al* (1993) which utilises Camp's three-parameter function (Camp, 1946) for determining the trap efficiency. Vetter's formula is used to adjust for short-circuiting and basin turbulence (Vetter, 1940).

The use of estimated pollutant partition coefficients (and/or particle size weightings) derived from the literature for metals, hydrocarbons etc., can also be applied to derive an approximation of other toxic species removal rates. Table B2 provides estimates

Table B2. Pollutant Load Fractions Attached to Stormwater Solids

Pollutant	Percentage Solids Partitioning
BOD	60 - 70
COD	75 - 85
Bacteria	80 - 90
Hydrocarbons	65 - 75
Zinc	30 - 45
Lead	75 - 85

of the range of observed pollutant loads attached to stormwater sediment, mainly associated with the finer particle size fractions below 0.05 mm. Adjustments can be made to the solids retention results obtained from the calculations in Section 3 above to derive an estimate of the retention efficiencies for the various toxic pollutant species noted in Table B2.

5. Empirical Approaches to Solids Removal

5.1 Solids removal is essentially a function of sedimentation i.e. (bio)infiltration and retention time, which is primarily affected by the relationships between size and settling velocity (Section 2 above). A number of empirically derived regression equations have been derived to predict solids removal efficiency for SSF wetlands in the absence of detailed data on influent particle size distribution and settling velocities (V_s). The two most widely used are those associated with the US NADB (Knight *et al.*, 1993) and UK/Denmark wetland databases (Brix, 1994):

$C_{Sout} = 4.7 + 0.09\, C_{Sin}$ (Brix, 1994)
$C_{Sout} = 7.8 + 0.063\, C_{Sin}$ (Knight *et al.*, 1993)

Reed (1994) has also suggested:

$C_{Sout} = C_{Sin}\,[(0.1058 + 0.0011)\ \mathrm{HLR\ (cm/day)}]$

5.2 Taking the wetland design data from Section 2.2, Appendix C and the derived HLR value (0.043 m/d) of Section 2.3 in Appendix C, and assuming a TSS influent concentration (C_{Sin}) of 100 mg/l, the Reed equation derives an outflow (C_{Sout}) concentration of:

$$C_{Sout} = 100\,[\{(0.1058 + 0.0011)\ 4.3\}] = 46\ \mathrm{mg/l} = 54\%\ \text{removal efficiency}$$

The UK/European and US NADB equations derive C_{Sout} values of 5.6 mg/l and 14.1 mg/l respectively i.e a 94% and 86% removal efficiency.

Additional References

BRIX, H. 1994. Use of constructed wetlands in water pollution control: Historical development, present status and future perspectives. *Wat. Science & Tech.*, 30, 209 – 223.

CAMP, T R. 1946. Sedimentation and the design of settling tanks. *Trans, Amer. Soc. Civil Eng.*, 111, 895 - 952.

VETTER, C P. 1940. Technical aspects of the silt problem on the Colorado river. *Civ, Eng.*, 10 (11), 698 - 701.

APPENDIX C

KINETIC DESIGN MODELLING OF WETLANDS

(See Sections 2.1.5 and 3.2.2 in main text)

1. Introduction

1.1 Plug flow is generally considered to be the optimal flow condition for a wetland and is from a hydraulic viewpoint the preferred flow regime since all fluid elements reside around the normal residence time. Further, the removal rates of pollutants such as BOD, SS and nitrogen increase with the loading rate, which makes plug flow more desirable. Mathematically, plug flow can be defined as a residence time distribution (RTD) with a variance (σ^2) equal to zero i.e no dispersion other than the advection, and a quotient between mean time (t_{mn}) and nominal residence time (t_{nom}) which equals unity i.e no dead zones.

1.2 The generalised plug flow input/output reactor k - C^* model is given in the box in Section 1.7 as: $(-k/HLR) = \ln[(C_{out} - C^*) / (C_{in} - C^*)]$ and where the Hydraulic Loading Rate (HLR) = (Q_{in} / A_s); see third box in Section 1.6.3. Re-arrangement (with appropriate unit conversion) of this general model therefore provides a basis for determining the required surface area (A_s) of a SF wetland basin intended for the removal of a particular pollutant:

$$A_s = (Q/k) \ln[(C_{in} - C^*) / (C_{out} - C^*)]$$

1.3 Reed *et al* (1995*)* have also proposed a simplified kinetic design equation which places k into the numerator of the equation, and that can be used for preliminary estimation of SSF wetland sizing:

$$A_s = Q (\ln C_{out} - \ln C_{in}) / kD$$

where D is the free water depth (ρ x d); see boxes in Section 1.6.3.

2. Wetland Sizing

2.1 As an example, it is intended that a stormwater SF wetland should reduce the long-term inlet annual average Total Nitrogen (N_{tot}) concentration from 4.5 mg/l to a target outlet concentration of 1.6 mg/l for an average influent discharge (Q_{in}) of 25.8 m^3/d. What surface area (A_s) of wetland will be required? No values are given for the nitrogen decay rate constant (k_{Ntot}) or for the wetland background concentration (C^*) but reference to Table 3.1 gives values of 22 m/yr and 1.5 mg/l respectively for these two parameters.
Applying and re-arranging the general equation:

$$A_s = [(25.8 \text{ x } 365) \ln\{(4.5 - 1.5) / (1.6 - 1.5)\}] / 22$$
$$= 1{,}455.86 \text{ m}^2 = 0.15 \text{ ha}$$

It should be noted that the effect of ignoring the background C^* value would give a much smaller surface area (A_s) value of 0.046 ha. Reduced winter temperatures will also reduce the k value, thus leading to a requirement for larger surface areas. For example, with a mean winter temperature of 5^o C (see box in Section 1.7) and still ignoring the background C^* value:

$$k_{Ntot} = 20\ (1.09)^{(5 - 20)} = 10.6 \text{ m/yr}$$

which would yield a wetland surface (A_s) value of 0.095 ha (i.e twice as large).

2.2 A 0.6m deep SSF wetland with substrate porosity of 0.4 (40%) receives an average daily flow of 60.5 m^3/d with an influent BOD concentration of 140 mg/l and has an outflow target concentration of 10 mg/l. The prevailing winter temperature is 10^o C and the reaction rate constant (k) is 1.104 days at 20^o C. What surface area (A_s) is needed to meet the target concentration?

$$k_{BODt} = 1.104\ (1.09)^{(10 - 20)} = 0.47/\text{day}$$

$$\text{and } A_s = 60.5\ (\ln 140 - \ln 10) / (0.47 \times 0.6 \times 0.4) = (160 / 0.113)$$

$$= 1416 \text{ m}^2$$

2.3 An alternative non-kinetic approach to the sizing of SSF wetlands has been suggested by Reed (1993) which is based on the premise that in a "temperate" climate, the annual BOD removal rate approximates 2.5 kg/m^2/yr. Using the design information provided in Section 2.2 above, the annual BOD removal for the wetland would be: $[(C_{in} - C_{out})\ (Q/1000)]\ 365$

$$= [(140 - 10)\ (60.5 / 1000)]\ 365 = 2{,}871 \text{ kg/yr}$$

$$\text{and } A_s = (2871 / 2.5) = 1148 \text{ m}^2$$

which is within 20% of the 1416 m^2 figure derived from the kinetic procedure, and HLR = (Q / A_s) = (60.5 / 1416) = 0.043 m/d (= 4.3 cm/day)

3. Pollutant Decay Rates and Removal Efficiency

3.1 For the general pollution reduction rate (J) equation given in section 1.7:

$$J = -k\ (C_{in} - C^*)$$

and the pollutant mass balance equation, assuming plug flow conditions, for the wetland also can be expressed as:

$$HLR\ (\partial C_{in} / \partial x) = -k\ (C_{in} - C^*)$$

with the pollutant fraction remaining (F_R) in the wetland of the total possible change in pollutant (see box in Section 1.7) then being:

$$F_R = [(C_{out} - C^*) / (C_{in} - C^*) = e\ [(-k / HLR)]$$

3.2 The decay rate (k) for Total Nitrogen (N_{tot}) removal in a wetland is 31.7 m/yr at a determined HLR value of 28.65 m/yr. What is the pollutant fraction remaining (F_R) in the wetland?

$$F_R = [(C_{out} - C^*) / (C_{in} - C^*)] = e^{(-k / HLR)}$$

$$= e^{(-31.7 / 28.65)}$$

$$= 0.031$$

Therefore the percentage of total nitrogen retained within the wetland as a result of these conditions would be 33.1%.

Note that the combined dimensionless value (-k / HLR) is also known in many textbooks (e.g. Kadlec and Knight, 1995) as the Damkohler number (Da)

3.3 A SSF wetland is designed for a maximum stormwater discharge of 300 m^3/d with hydraulic retention time (HRT) of 4 days. The gravel (Diameter, Dp = 10mm) substrate has a porosity (ρ) of 40% and the average water depth (d) is 0.55m.

From the first box in Section 1.6.3, HRT = (LWD) / Q = ($A_s d\rho$ / Q)

$$4 = [(LW \times 0.55 \times 0.4) / 300] \text{ and as } LW = A_s$$

$$A_s = 5455 \text{ m}^2 \text{ and with } HLR = (Q / A_s)$$

$$HLR = 300 / 5455 = 0.055 \text{ m/d}$$

With a particle size of 10mm, the hydraulic conductivity (k_h) can be estimated as (see the last box in Section 3.2.2):

$$k_h = 12{,}600\,(0.01)^{1.9} = 2.0 \times 10^{-2} \text{ m/s}$$

3.4 The first-order kinetic plug flow reaction model can be used to predict the pollutant removal efficiency using the alternative form of the general model as shown in the box in Section 2.1.5:

$$C_{out} = C_{in}\, e\, [(-k / HLR)]$$

For the 1.3 ha Anton Crescent SF wetland in Sutton, Surrey, Cutbill (1997) calculated that the mean inlet concentration for Total Coliforms was 1990 MPN/100ml with an average annual HLR of 13.33 m/yr and decay rate k value of 19.89 m/yr. Therefore:

$$C_{out} = 1990\, e\, [(-19.89 / 13.33)] = 448 \text{ MPN/100ml}$$

$$= 77\% \text{ average annual removal rate}$$

Figure C1 illustrates the removal efficiency for varying hydraulic loading rates (HLR) values ranging from 1 up to 1,000 m/yr. The figure shows that the SF wetland is able to reduce bacterial concentrations effectively up to HLR rates of about 100 m/yr although 65% removal can be expected at rates of less than 12 m/yr.

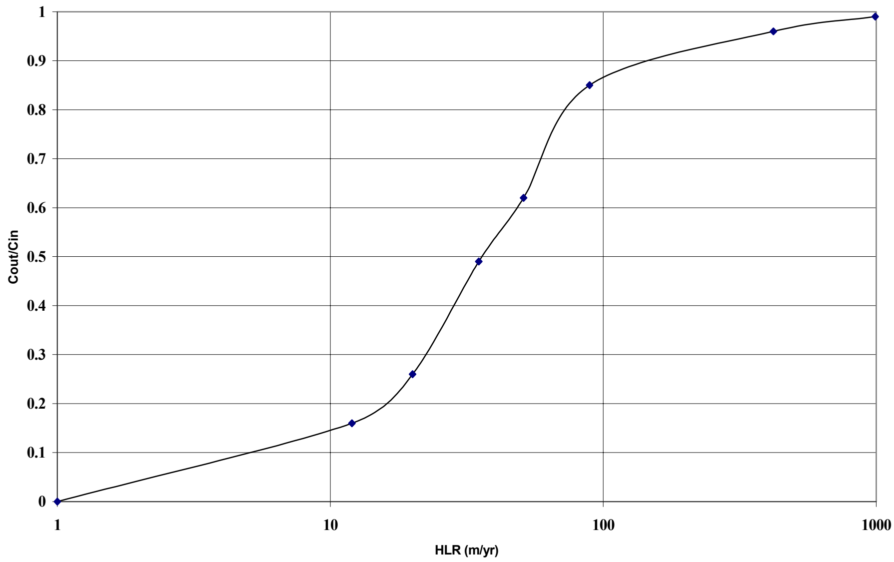


Figure C1. Bacterial Removal Efficiency and Hydraulic Loading Rate

Additional References

REED, S C. 1993. *Subsurface flow constructed wetlands for wastewater treatment*. Report EPA832-R-93-008, Environment Protection Agency, Washington DC, USA.

APPENDIX D

SURFACE WATER DISCHARGE, SEDIMENT QUALITY STANDARDS AND RECEVING WATER CLASSIFICATION IN ENGLAND & WALES

1. Discharge Standards and Consents for Surface Waters in England & Wales

1.1 Section 95 of the 1991 UK Water Industry Act states the general duty of sewerage undertakers is to "*provide, improve and extend…….a system of public sewers"*…. to achieve effectual drainage within urban areas. This duty includes the requirement to collect and dispose of surface water. Outfalls from separate (surface water) sewers are not subject to routine consent in the UK although under Section 85 of the 1991 Water Resources Act it is an offence to "*cause or knowingly permit any poisonous, noxious or polluting matter or any solid waste matter to enter any controlled waters*". Section 100 of the 1980 Highways Act gives the right to discharge road runoff to surface waters through highway drains (which include ditches, gutters, culverts and pipes).

1.2. However, under Section 89 (5) of the 1991 Water Resources Act (WRA), the highways authority does not require the statutory defence of a discharge consent although the 1998 Groundwater Regulations (which implement the EU Directive 80/68/EEC), does impose specific requirements. It should be noted that the exemption status for stormwater drainage does not apply in Scotland where they were taken out of direct control as a deregulation initiative at the time that the Scottish Environment Protection Agency (SEPA) was established. Measures required to prevent or alleviate pollution are usually agreed through consultation between the highways authority and the Environment Agency and a policy implementation guidance note (SC/CC/014) for highway discharges was issued in September 1992. The Environment Agency and Highways Agency have a Liaison Agreement in place which sets out their joint understanding of the relevant legislation and arrangements for early consultation on the effects of new and improvement schemes and maintenance works on the water environment. This is currently being updated and is intended to become a formal Memorandum of Understanding or Advice Note. The criminal defence against highway discharges embodied in Section 89 (5) WRA 1991 does not hold against liabilities arising under civil law where pollution can be shown and proven to be "*caused or knowingly permitted*".

1.3 The Environment Agency can choose to apply the provisions of Section 86 of the WRA 1991 to serve a Conditional or Absolute Prohibition Notice to an existing surface water outfall (SWO), if it saw fit to do so because of some particular pollution hazard. This could either require that a consent be obtained (under Schedule 10, para 5 (1), WRA 1991) or alternatively the Agency may specify the conditions to be observed prior to the approval of a discharge. SEPA has a similar fall-back power of serving a prohibitive Notice requiring pollution prevention measures; the only defence against an Absolute Prohibition Notice being a discharge consent. On the basis of the limited information available at the time of writing this report, there are about 50,000 SWOs in the UK of which some 7% (about 3540) are consented. Where surface water discharges are highlighted as a cause of receiving water quality problems, a similar approach to that applied to combined sewer overflows (CSOs) is likely to be adopted based on discharge frequency-duration-magnitude relationships.

1.4 The consenting approach includes the assessment of the effects of short duration pollution pulses on the aquatic biota together with consideration of aesthetic requirements (e.g no visible oil, gross solids limitation etc..). The nature and form of surface water outfall (SWO) consents is therefore likely to be similar to those set for combined sewer overflows (CSOs) and the Environment Agency may also set conditions for treatment in a consent. The conceptual regulatory approach to such intermittent, wet weather storm discharges that has been adopted in the UK Urban Pollution Management (UPM) Manual, is one of environmental quality standards linked to use-related objectives (FWR, 1998). Three major water-related uses have been identified as being potentially affected by CSOs and SWOs:

- River Aquatic Life; where short periods of low DO and/or high un-ionised ammonia can hinder the development of a sustainable fishery in inland waters
- Bathing; where frequent and persistent high bacterial concentrations can cause non-compliance with the EU Bathing Directive standards
- General Amenity; where gross solids and litter can lower the perceived quality of the receiving water body resulting in public complaints

1.5 Environmental quality standards for intermittent discharges have been developed (FWR, 1998) for River Aquatic Life based on intensity/duration/frequency relationships for DO and un-ionised ammonia and are illustrated in Table D1. The intermittent standards in the table give allowable return periods for specified DO and ammonia thresholds. For example, the minimum return period for DO falling below 4 mg/l for a 1 hour spillage period is one month i.e such an event should not happen more frequently than 12 times a year on average. The UPM Manual standards are based on literature information and the results of ecotoxicological investigations based on viability of fish and invertebrate communities.

Table D1. Standards for Intermittent Discharges

<table>
<tr><th rowspan="3">Flow Return Period</th><th colspan="4">Dissolved Oxygen (DO) Concentration (mg/l)</th><th colspan="3">Ammonical Nitrogen (NH_3-N) (mg/l)</th></tr>
<tr><th colspan="4">Exposure Period</th><th rowspan="2">1 Hour</th><th rowspan="2">6 Hours</th><th rowspan="2">24 Hours</th></tr>
<tr><th>0.25 hours</th><th>1 Hour</th><th>6 Hours</th><th>24 Hours</th></tr>
<tr><td>1 Week</td><td>4.0</td><td>6.0</td><td>7.0</td><td>7.5</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>1 Month</td><td>3.5</td><td>4.0</td><td>5.0</td><td>5.5</td><td>0.175</td><td>0.100</td><td>0.040</td></tr>
<tr><td>3 Months</td><td>3.0</td><td>3.5</td><td>4.5</td><td>5.0</td><td>0.250</td><td>0.150</td><td>0.060</td></tr>
<tr><td>1 Year</td><td>2.7</td><td>3.0</td><td>4.0</td><td>4.5</td><td>0.275</td><td>0.175</td><td>0.075</td></tr>
</table>

With the introduction of the General Quality Assessment (GQA) approach for receiving water quality classification in England & Wales (See Section 2 and Figure D1 below), it has been necessary to develop intermittent standards which fit the new River Ecosystem (RE) groupings. The new Fundamental Intermittent Standards

(FISs), follow the approach illustrated in Table D1, but have been extended to cater for three types of ecosystem:

- sustainable salmonid fishery
- sustainable cyprinid fishery
- marginal cyprinid fishery

In practice, the tabulated standards are generally modified by using correction factors for individual sites and events to account for ambient environmental conditions and interactions between pollutants. The criteria for a sustainable salmonid fishery in respect of a 6 hour duration episode having a 1 year return period (RI), is shown in Table D2.

Table D2. Fundamental Intermittent Standards for Ecosystem Types

Ecosystem Type	Dissolved Oxygen (mg/l)	Un-ionised Ammonia (mg/l)
Sustainable salmonid fishery	4.5	0.04
Sustainable cyprinid fishery	4.0	0.15
Marginal cyprinid fishery	2.5	0.20

As an alternative to FIS, the UPM procedure identifies 99 percentile criteria that may be related to the River ecosystem (RE) classes. These values are shown in Table D3 for BOD, total ammonia and un-ionised ammonia and are based on an extrapolation of the RE class 90/95 percentile criteria.

Table D3. Pollutant 99 Percentile Values for RE Classes

RE Class	**BOD** (mg/l) 99 percentile	**Total Ammonia** (mg/l) 99 percentile	**Un-ionised Ammonia** (mg/l) 99 percentile
RE1	5.0	0.6	0.04
RE2	9.0	1.5	0.04
RE3	14.0	3.0	0.04
RE4	19.0	6,0	
RE5	30.0	25.0	

The Environment Agency's policy for the choice of which criteria to apply, depending on the significance of a discharge and following the approach adopted for AMP2, is set out in a separate document (Environment Agency, 2000). Depending on site-specific circumstances, solutions could be required to be compliant with either or both types of criteria.

1.6 The environmental standards for protection of Bathing Waters are well known from the EU Directive which is being currently reviewed. As yet no inland waters within the UK have been designated under the terms of the Directive and as such surface water outfalls discharging to recreational receiving waters are not strictly subject to the Directive. However, the acceptable duration of non-compliance due to storm discharges would be about 1.8% of the "bathing or recreational season". An alternative emission-based approach has been developed for CSOs in the form of a simple spill frequency criterion, expressed as not more than three spills on average per "bathing season" (NRA, 1993).

1.7 The Environment Agency Regions Complaints Registers indicate that urban runoff is the source of some 2 - 10% of public complaints compared to 5 - 20% in the case of sewage-related pollution associated with CSOs (FWR,1996). Aesthetic pollution caused by intermittent urban discharges can be judged on the basis of litter, refuse, colour, odour, visible oil, foaming and excessive fungal growth in the receiving water below a combined sewer overflow or surface water outfall discharge point.

1.8 It should be noted that fundamental change to the current UK water quality legislation will take place with the rolling implementation of the EU Water Framework Directive over the next five years or so. It is not as yet at all clear what the implications or effects of the new legislation will have on procedures for approving and/or consenting surface water discharges although it may be that the Environment Agency will wish to adopt a Supplementary Measures approach under the Directive using "general binding rules" to tackle diffuse pollution accompanied by more extensive and targeted Codes of Practice embodied in revised Pollution Prevention Guidelines (PPGs); see Section 6.2.2.

2 Receiving Water Quality Classification in England & Wales

2.1 Under the provisions of the 1991 Water Resources Act, the National Water Council (NWC) classification scheme of absolute measures of receiving water quality has been replaced with a General Quality Assessment (GQA) to be applied to a given river reach and a Rivers Ecosystem (RE) classification for the statutory Water Quality Objectives (WQOs) required to meet specified local use-related needs. The former GQA addresses four main categories (or Windows) covering General Chemical, Nutrients, Biological and Aesthetic Quality whilst the RE classification establishes clear quality targets (and specified compliance dates) for all controlled waters on a statutory basis.

2.2 Only the general Chemical Window is currently in place and only for a limited number of determinands although the structure of the Biological Window has recently been issued in draft form and is based on a comparison of the observed freshwater invertebrate fauna at a site with that which would be expected if no pollution was present. Figure D1 shows the structure of and relationships between these new water quality assessment approaches and the previous NWC system. In the event that both a WQO and a GQA exists for a particular water, then the Environment Agency will be legally obliged within a specified period, to improve the water quality such that the GQA is similar or better than the WQO equivalent parameters. As such therefore, the statutory WQO of the receiving water will dictate the treatment level required for surface water discharges (including urban and highway runoff).

2.3 Where statutory WQOs do not exist, either the GQA or interim, non-statutory WQOs will be used. Where a stream reach supports more than one use-function, and where both statutory and non-statutory water quality requirements pertain, the most stringent of the combined specifications will apply. Therefore the assessment of new roads or road improvements must include consideration of all the uses (both upstream and downstream) to which the watercourse is put.

3 Sediment Quality Standards

3.1 Wetland SuDS structures will accumulate contaminated sediment including toxic metals which will ultimately require disposal and thus become subject to prevailing regulatory limits for contaminated soil and biosolids. Table D2 gives "trigger" or threshold loading limits as defined under EU legislation for biosolids and soil expressed in either annual or total cumulative loadings. As a basis for comparison with the standard EU limits, the table also shows regulatory limits that have been established elsewhere and which are often referred to in the literature.

3.2 The UK Inter-Departmental Committee on the Redevelopment of Contaminated Land (ICRCL) values are those quoted for parks and open spaces whilst the Dutch values are those defining clearly contaminated land. Even adopting the maximum loading rates shown in the table would suggest that the operational lives of most wetlands would be at least 20 - 50 years especially if given regular and proper maintenance. However, the relatively low loading limits specified for cadmium might provide a more critical restriction.

Table D4. Sediment Quality Standards

Pollutant	**UK ICRCL** (mg/kg)	**EU 1986 Directive**				**Dutch Ministry of Public Housing** (mg/kg)	**Swedish EPA** "Moderate pollution" (mg/kg)	**US EPA** 503 Regulations (kg/ha/yr)	**Canada** Ontario Ministry of Env. (Lowest Effect Level) (mg/kg)
		Biosolids (mg/kg)	UK 90% (1996/97) Biosolids Limit	Soil (mg/kg)	Application Loading 10 yr average (kg/ha/yr)				
Zinc	300	2500 - 4000	1076	150 - 300	30	720	175 - 300	140	110.0
Lead	2000	750 - 1200	288	50 - 300	15	530	30 - 100	15	31.0
Cadmium	15	20 - 40	3.4	1.3	0.15	12	1.7 - 2.0	1.9	1.0
Copper		1000 - 1750	758	50 - 140	12		25 - 50		25

Additional References

FWR. 1996. *Assessing the benefits of surface water quality impacts manual*. FR/CL0005. Foundation for Water Research, Medmenham, Bucks.

FWR. 1998. *Urban pollution management manual*. (2nd Edition), Foundation for Water Research, Medmenham, Bucks.

ENVIRONMENT AGENCY. 2000. *Procedure for consenting intermittent discharges*. Environment Agency, Bristol.

NRA. 1993. *Guidelines for AMP2 periodic review*. (Version 2). National Rivers Authority, Bristol

WATER QUALITY ASSESSMENT SCHEMES
(Formerly consolidated within the NWC scheme)

GENERAL QUALITY ASSESSMENTS (GQA)
(For survey assessment purposes)
Will consist of **FOUR** separate **WINDOWS** as given below

WATER QUALITY OBJECTIVES (WQOs)

(On pass/fail basis for management purposes)

2. NUTRIENTS

1. CHEMICAL

3. BIOLOGICAL QUALITY

RIVER ECO-SYSTEM (RE) WQOs

Former NWC System

3. Biological Quality	Water Quality	GRADE	DO % Sat 10%ile	BOD mg/l 90%ile	Total Ammonia mg/l 90%ile	Total Zinc µg/l 95%ile	Dissolved Copper µg/l 95%ile	Hardness mg/l $CaCo_3$	RIVER ECO-SYSTEM (RE) WQOs	Former NWC System
A Better than expected; high diversity; several species in each taxa	Very Good	A	80	2.5	0.25	30 200	5 22	≤10 10 - 50	**RE1**	**1a**
B Short of expected; small reduction in pollution tolerant taxa	Good	B	70	4	0.60	300 500	40 112	50 - 100 >100	**RE2**	**1b**
C Worse than expected; many sensitive species absent; rise in pollution tolerant taxa	Fairly Good	C	60	6	1.3	300 700	5 22	≤10 10 - 50	**RE3**	**2**
D Worse than expected; sensitive taxa scarce; some pollution tolerant species in large numbers	Fair	D	50	8	2.5	1000	40	50 - 100	**RE4**	
E Restricted to pollution tolerant species; a few taxa dominant; sensitive taxa rare or absent	Poor	E	20	15	9.0	-	-	-	**RE5**	**3**
F Limited to few pollution tolerant taxa; or no life present	Bad	F	-	-	-	-	-	-		**4**

4. AESTHETIC QUALITY

Figure D1 Water Quality Assessment Schemes

APPENDIX E
See Section 4.1.2 in main text

OUTLINE INSPECTION SHEET: WETLAND OPERATION, MAINTENANCE & MANAGEMENT

Name/Location:…………………………………. Site status:…………………………………………
Site Manager/Landscape Foreman:……………………………..Reporting Office/Tel:…………………

ITEM	FREQUENCY	SATISFACTORY or UNSATISFACTORY	TICK (when work done)	DATE	INITIAL
Wetland Vegetation					
– **maintain 50% surface area coverage of wetland plants after 2nd growing season**	Annually				
– **new plantings**	As necessary				
– Dominant wetland plants; distribution according to landscape plan?	As necessary				
– Evidence of invasive species	Annually				
– Water depth; (maintain adequate water depths for desired wetland plant species)	As necessary				
– Plant removal; dead plants and/or "choked" by sediment build-up	As necessary				
– Evidence of eutrophication	As necessary				
Pre-Treatment Pool/Sediment Forebay					
- sediment removal (Depth < 50% design depth	As necessary				
Inlet(s)					
- riprap	Annually				
- litter screens	Quarterly*				
- blockages	As necessary*				
- pontoons	Annually				
- booms	As necessary				
- stilling area	As necessary				
Outlet(s)					
- riprap failure	Annually				
- litter screens	Quarterly*				
- drain pipes	Annually				
- blockages	As necessary*				
- endwalls/headwalls	Annually				
- slope erosion	Annually				
- drop manhole	Annually*				
- valves	Annually				
Riser Pipe					
- orifice obstruction	Annually*				
- cracking/spalling/corrosion	Annually				
- sediment accumulation in riser	Annually*				
- control/drain valves	Annually				
Wetland Pool					
- floatables/gross debris	Annually*				
- visible pollution e.g. oil	As necessary*				
- shoreline erosion	As necessary				
Peripheral Slopes/Buffer Zone					
- grass mowing	As necessary				
- erosion/rabbit and animal burrows	Annually				
- prune shrubs/trim edges etc	Annually				
- spraying (*Separate note below if undertaken*)	As necessary				
Other					
- signage problems (vandalism, repair etc.)	As necessary				
- boardwalks/seating	As necessary				
- fencing	As necessary				
- grafitti	As necessary				
- condition of access route(s)	Annually				
- complaints (*Separate note below*)	As necessary				
- other public hazards (*Separate note below*)	As necessary				

NOTES/COMMENTS……………………………………………………………………………………………
………
………
………
………

Signature:…………………………………. **Position/Status:**……………………………. **Date:**………………..

*** = Also after Major Storms**